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# Power Plant Impacts on Air Quality and Visibility: Siting and Emission Control Implications

**Systems Applications, Inc, San Rafael, CA**

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# POWER PLANT IMPACTS ON AIR QUALITY AND VISIBILITY: SITING AND EMISSION CONTROL IMPLICATIONS

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401 M Street, S.W.
Washington, D.C. 20460

Prepared by

Douglas A. Latimer

Systems Applications, Incorporated
950 Northgate Drive
San Rafael, California 93902

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The air quality and visibility impact of various sizes of power plants, which emit $SO_2$ and $NO_x$ at various rates, was analyzed using analysis methods either recommended or likely to be accepted by the EPA. The impact of single power plant plumes and cumulative emissions on a regional scale were considered. Tentative conclusions are made regarding the air quality and visibility impacts of power plants individually and collectively throughout a region and the implications of these impacts for power plant sitings and emissions control.

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# ERRATA

On page v of Table of Contents please change "100 Mwe" and "300 Mwe" to "1000 Mwe" and "3000 Mwe," respectively.

# DISCLAIMER

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# I INTRODUCTION

On 19 September 1978, the Environmental Protection Agency (EPA) published in the Federal Register proposed standards of performance for new electric utility steam generating units (power plants) to revise current emission standards. In addition to making the standards for nitrogen oxide and particulate emissions more stringent, the standards require that uncontrolled $SO_2$ emissions be reduced by 85 percent. The intent of these regulations is to require new power plants "to use the best demonstrated systems of continuous emission reduction," namely, flue gas desulfurization ($SO_2$ scrubbers).

In proposing these regulations, the EPA has stated (Federal Register, 1978a, p. 42154):

> The principal issue associated with this [emission standard] proposal is whether electric utility steam generating units firing low-sulfur-content coal should be required to achieve the same percentage reduction in potential $SO_2$ emissions as those burning higher sulfur content coal. Resolving this question of full versus partial control is difficult because of the significant environmental, energy, and economic implications associated with each alternative [emission standard].

In November 1978, the EPA's Office of Planning and Evaluation contracted with Systems Applications, Incorporated (SAI) to study the air quality and visibility implications of alternative New Source Performance Standards (NSPS) for $SO_2$. This report describes that study and the conclusions reached regarding the impacts on air quality, visual range, and atmospheric discoloration and the constraints on power plant siting resulting from alternate $SO_2$ emission control requirements.

We studied three alternate $SO_2$ emission floors (i.e., maximum required control levels): 0.2, 0.5, and 0.8 pounds of $SO_2$ per million Btu heat input ($lb/10^6$ Btu). In addition, we investigated the emission ceiling for coal (or lignite) of 1.2 $lb/10^6$ Btu.

In this study, we attempted to answer the following questions:

- > What will be the air quality impacts associated with new power plants meeting alternate emission standards?
- > Will these impacts cause exceedances of Prevention of Significant Deterioration (PSD) Regulations?
- > What will be the impact of alternate emission regulations on visibility impairment (including reductions in visual range and atmospheric discoloration)?
- > What are the implications of alternate $SO_2$ emission regulations on power plant siting?
- > What is the maximum regional power plant siting capacity?
- > How close can a power plant be sited to a Class I (pristine) area without causing significant visibility impairment or exceedances of PSD increments?
- > How close can a power plant be sited to elevated terrain without causing violations of PSD Class I, II, or III increments or National Ambient Air Quality Standards (NAAQS)?
- > What are the implications for power plant siting in the regions of the western United States where the terrain is complex and the number of Class I areas is large?

To address these questions, we used analytical techniques and models that were either recommended by or likely to be accepted by the EPA. Because of the generic nature of this study, no attempt was made to provide refined estimates based on area-specific meteorology and terrain; the results of this study should be examined in that context. This study is not meant to substitute for more detailed, site-specific analyses of impacts on air quality and visibility and the resultant implications for siting and emissions control.

Chapter II of this report outlines the basis for our air quality and visibility calculations. Chapter III describes the impacts of individual power plants, and Chapter IV outlines estimated cumulative regional impacts resulting from regional power plant development. Chapter V then summarizes the conclusions of our study.

# II BASES FOR CALCULATIONS

This chapter outlines the methodology, assumptions, and techniques used in our study. These bases for calculations can be categorized as follows:

> Power plant emission conditions
> Air quality and PSD Regulations
> Meteorological scenarios and air quality modeling
> Visibility modeling.

## A. EMISSION CONDITIONS

We evaluated air quality and visibility impacts for several sizes of power plants: 500, 1000, 2000, and 3000 Mwe. The power plants of larger capacity were assumed to consist of multiple 500 Mwe units, an average size for new coal-fired boilers. The 3000 Mwe size is believed to be the largest capacity likely to be installed at a given site. The 1000 Mwe size is probably representative of a small power station, and the 2000 Mwe size (consisting of four 500 Mwe boilers) is believed to be most typical of developments at a single site.

Power plant emission conditions for this study were selected by the EPA based on the assumption that the power plant would be equipped with $SO_2$ (wet) scrubbers and stack heights representing "good engineering practice." Power plant emission conditions were assumed as follows:

| Variable | Value |
|---|---|
| Stack height | 500 ft |
| Number of stacks per boiler | 1 |
| Flue gas temperature | 175°F (scrubbed temperature of 125°F plus 50°F reheat) |
| Flue gas flow rate | 2540 acfm/Mwe at 175°F (1,270,000 acfm per stack) |
| Overall power plant heat rate | 9000 Btu/kwh (equivalent to a thermal efficiency of 38%) |

$SO_2$ emission rates of 0, 0.2, 0.5, 0.8, and 1.2 pounds per million Btu and $NO_x$ emission rates of 0, 0.2, 0.5, 0.6, and 0.8 pounds (as $NO_2$) per million Btu were evaluated. Although the particulate (fly ash) emission standard is 0.03 $lb/10^6$ Btu, we found that the 20 percent opacity standard is the most restrictive on the particulate emission rate. (The opacity requirement limits particulate emissions to 70 percent of 0.03, or 0.02 $lb/10^6$ Btu.)

A simple formula can be used to express the overall mass emission rates as a function of emission standards and power plant size:

$$\begin{aligned} Q_o &= (E\ \mathrm{lb}/10^6\ \mathrm{Btu})\ (P\ \mathrm{Mwe}) \\ &\quad \times (9000\ \mathrm{Btu/kwe\text{-}hr})\ (1000\ \mathrm{kwe/Mwe}) \\ &\quad \times (453.6\ \mathrm{g/lb})\ (1\ \mathrm{hr}/3600\ \mathrm{sec}) \\ &= 1.134\ (E)(P)\ (\mathrm{g/sec}) \quad . \end{aligned}$$

It is instructive to compare the $SO_2$ emission rates evaluated ($0 < E < 1.2\ lb/10^6$ Btu) to the rates that would result from the combustion of various types of coal. Table 1 indicates the sulfur content, heating value, and resulting uncontrolled and controlled $SO_2$ emission rates in pounds per million Btu for several typical U.S. coals. Note that several low-sulfur coals, after 85 percent $SO_2$ control, result in emissions of less than 0.2 $lb/10^6$ Btu; however, use of a Midwest (Illinois) coal would cause $SO_2$ emissions to be almost at the emission ceiling of 1.2 $lb/10^6$ Btu. Thus, the various $SO_2$ emissions considered in our study could result from the imposition of alternative floors (0.2, 0.5, and 0.8 $lb/10^6$ Btu) or from 85 percent control of a high-sulfur coal, irrespective of the $SO_2$ floor.

## TABLE 1. SUMMARY OF TYPICAL U.S. COALS AND RESULTING $SO_2$ EMISSIONS

| Type of Coal | Sulfur Content* (percent) | Heating Value* (Btu/lb) | $SO_2$ Emission Rate ($lb/10^6$ Btu) | |
|---|---|---|---|---|
| | | | Uncontrolled | 85% Control |
| Anthracite (Pennsylvania) | 0.8 | 12,880 | 1.24 | 0.19 |
| Semi-anthracite (Arkansas) | 1.7 | 13,880 | 2.45 | 0.37 |
| Bituminous | | | | |
| Pensylvania | 1.0 | 14,310 | 1.40 | 0.21 |
| Kentucky | 2.8 | 11,680 | 4.79 | 0.72 |
| Illinois | 3.8 | 10,810 | 7.03 | 1.05 |
| Subbituminous | | | | |
| Wyoming | 0.5 | 9,610 | 1.04 | 0.16 |
| Colorado | 0.3 | 8,560 | 0.70 | 0.11 |
| Lignite (North Dakota) | 0.9 | 7,000 | 2.57 | 0.39 |

---

* Source: Ode (1967).

## B. AIR QUALITY AND PSD STANDARDS

To evaluate power plant impacts on ambient air quality, we compared calculated ground-level $SO_2$ concentrations with the following National Ambient Air Quality Standards and PSD increments:

| Standard | $SO_2$ Concentrations ($\mu g/m^3$) | |
|---|---|---|
| | 3-Hour Average | 24-Hour Average |
| PSD Class I | 25 | 5 |
| PSD Class II | 512 | 91 |
| PSD Class III | 700 | 182 |
| NAAQS | 1300 | 365 |

It can easily be shown that for power plants the $SO_2$ PSD increments and air quality standards, not those for particulate and $NO_2$, are most controlling. Furthermore, as shown in the next section, the 24-hour-average $SO_2$ PSD increments, rather than the 3-hour-average or annual average, are most restrictive based on the modeling approaches used in this study.

## C. METEOROLOGICAL SCENARIOS AND MODELING APPROACHES

In the 19 June 1978 Federal Register, the EPA referenced two documents that provide guidance on air quality modeling approaches to be used in evaluating power plant compliance with PSD Regulations (EPA, 1978; Budney, 1977). The EPA recommends Gaussian modeling approaches and various conservative screening techniques to determine whether there is a possibility of an exceedance of an ambient air quality standard.

The EPA stated (Federal Register, 1978b):

> . . . EPA's assessment of the air quality impacts of new major sources and modifications will be based on EPA's "Guidelines on Air Quality Models," OAQPS 1.2-080, U.S. Environmental Protection Agency, Research Triangle Park, N.C. 27711, April, 1978. This guideline is incorporated by reference into the regulations. Sources may request approval from the Administrator to use air quality dispersion models other than those noted in the "Guideline." If the Administrator determines that the model recommended in the "Guideline" and the model proposed by a source are comparable, the proposed model may be used. . . .
>
> EPA intends to retain the screening procedures set forth in "Guidelines for Air Quality Maintenance Planning and Analysis, Vol. 10 (Revised), Procedures for Evaluating Air Quality Impact of New Stationary Sources," (October 1977, U.S. EPA, Office of Air Quality Planning and Standards, Research Triangle Park, N.C. 27711). . . .
>
> [EPA] intends to limit generally the application of air quality models to a downwind distance of no more than 50 kilometers. This is because dispersion parameters commonly in use are based on experiments relatively close to sources, and extending these parameters to long downwind distances results in great uncertainty as to the accuracy of the model estimates at such distances. . . .
>
> However, since the 1977 Amendments provide special concern for Class I areas, any reasonably expected impacts for these areas must be considered irrespective of the 50 kilometer limitation or the above significance levels.

In our study, we used modeling approaches outlined in the EPA's "Guidelines for Air Quality Maintenance Planning and Analysis, Volume 10" (Budney, 1977). Estimates were made with these models using (1) conservative assumptions appropriate for screening analyses and (2) more realistic assumptions regarding the persistence of worst-case meteorological conditions. The Gaussian models used in this study have the following basic formulation:

$$\chi = \frac{fQ_o}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{\exp\left[-\frac{1}{2}\left(\frac{H+z}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{H-z}{\sigma_z}\right)^2\right]\right\} , \quad (1)$$

where

$\chi$ = pollutant concentration ($\mu g/m^3$),
$Q_o$ = pollutant emission rate (g/sec),
$f$ = concentration ratio factors for 3- and 24-hour averages, respectively, to account for persistence of meteorological conditions,
$\sigma_y$, $\sigma_z$ = Pasquill-Gifford dispersion coefficients, which are functions of atmospheric stability and downwind distance x,
$u$ = wind speed (m/sec),
$y$ = crosswind distance of receptor point from plume centerline (m),
$z$ = elevation difference between receptor point and the power plant site (m),
$H$ = effective plume height (m), equal to the stack height plus plume rise.

Using EPA-recommended plume rise models based on Briggs' formulation, we calculated effective plume heights ranging from 300 m for stable, light-wind or neutral, strong-wind conditions to 640 m for neutral, light-wind conditions.

One of the worst-case meteorological conditions occurs when plume mixing is limited by a stable layer at elevation $H_m$. In such a situation, the plume eventually becomes uniformly mixed vertically for $0 < z < H_m$:

$$\chi = \frac{fQ_o}{(2\pi)^{1/2}\sigma_y H_m} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \quad . \qquad (2)$$

Based on recommendations in the EPA guidelines document for screening analyses, we selected the following meteorological conditions to analyze worst-case atmospheric dispersion conditions:

> Limited mixing conditions, Pasquill C stability, $u = 2.5$ m/sec ($0 < x < 50$ km).
> Limited mixing conditions, Pasquill D stability, $u = 7.5$ m/sec ($0 < x < 100$ km).
> Stable conditions, Pasquill E stability, $u = 4$ m/sec ($0 < x < 100$ km).
> Plume impingement conditions, Pasquill F stability, $u = 2.5$ m/sec, 6-hour persistence within a 22.5° sector, EPA Valley Model (Burt, 1977)--appropriate for elevated terrain only ($0 < x < 50$ km).

Although the EPA plans "to limit generally the application of air quality models to a distance of no more than 50 km" (Federal Register, 1978b), we have used the guidance provided in the Volume 10 guidelines document (Budney, 1977) for estimating impacts at distances up to 100 km downwind. In addition, we found that evaluation of potential air quality impacts in Class I areas required estimation of the power plant impacts at distances more than 100 km from a plant site. Therefore, in addition to the EPA-recommended approaches for downwind distances up to 100 km, we used a model based on the following conservative assumptions to estimate impacts at distances greater than 100 km:

> Uniform concentration within a sector subtending 11.25°.
> Uniform concentrations in the vertical direction within the mixed layer ($0 < z < H_m$).
> Mixing depth $H_m$ of 1000 m.
> Wind speed $u_c$ so as to maximize the concentration at each downwind distance (see below).

- Depletion of the initial $SO_2$ flux $Q_o$ as a function of downwind distance (travel time) resulting from sulfate formation and $SO_2$ surface deposition.
- $SO_2$-to-$SO_4^=$ conversion rate k of 0.5 percent per hour.
- $SO_2$ surface deposition velocity $v_d$ of 1 cm/sec.

This model can be stated mathematically as follows:

$$\chi = \frac{fQ_o e^{-[k+(v_d/H_m)]x/u}}{2\tan\left(\frac{11.25°}{2}\right) x u_c H_m} \quad . \qquad (3)$$

We can find the wind speed $u_c$ at each downwind distance that maximizes $\chi$ by taking the derivative of $\chi$ with respect to u at each given downwind distance, setting the derivative equal to zero, and solving for $u_c$ as follows:

$$\frac{d\chi}{du} = C_1 \left[ \frac{\left(k + \frac{v_d}{H_m}\right) x}{u_c^3} - \frac{1}{u_2^2} \right] = 0 \quad . \qquad (4)$$

Thus, at any given distance x, the wind speed $u_c$ that maximizes the concentration is simply:

$$u_c = \left(k + \frac{v_d}{H_m}\right) x \quad . \qquad (5)$$

Substituting Eq. (5) into Eq. (3) and simplifying, we have:

$$\chi = fQ_o \left[ \left(0.535\right) \left(k + \frac{v_d}{H_m}\right) x^2 H_m \right]^{-1} \quad . \qquad (6)$$

Using the selected values for k, $v_d$, and $H_m$, we have the following formula for estimating power plant impacts at downwind distances x greater than 100 km:

$$\frac{\chi}{Q_o} = f\left(\frac{1.64 \cdot 10^{-4}}{x^2}\right) \text{sec/m}^3 \quad \text{when x is in km.} \qquad (7)$$

When Eq. (5) is evaluated for the values of parameters selected, one obtains:

$$u_c = (1.14 \cdot 10^{-2})\ x \text{ m/sec} \quad \text{when x is in km.}$$

Thus, maximum concentrations at 200 km are predicted to occur with a wind speed of 2.3 m/sec; such winds would transport emissions from the power plant to the receptor location in 24 hours. Also note from Eq. (7) that concentrations fall off with the square of the distance downwind. This relationship results for two reasons: With increasing downwind distance, (1) the plume width is assumed to increase linearly, and (2) the pollutant flux is decreasing owing to surface deposition and conversion to sulfate.

In this analysis we have attempted to use the same Gaussian models to make conservative estimates of air quality impacts, as suggested by the EPA for screening analyses, and more realistic ones based on our own judgment. We have done this by using two sets of values of the concentration ratio factor f, which converts peak, short-term concentrations to time-averages [see Eqs. (1) and (3)]. For the conservative screening analysis of worst-day impacts, we have used the values recommended by Budney (1977)--0.9 for 3-hour averages and 0.4 for the 24-hour average. For the more realistic estimate of worst-day impacts we have used a range of concentration ratio factors based on measurements near the TVA's power plants reported by Montgomery and Coleman (1975). For the 3-hour average we use values ranging from 0.25 (TVA's 50 percentile) to 0.56 (95 percentile; exceeded 5 percent of time). For the 24-hour average we used values ranging from 0.05 (50 percentile) to 0.13 (95 percentile).

Based on the analysis by Holzworth (1972), the worst-case limited mixing condition with mixing depths less than 1000 m and wind speed less than 4 m/s can occur 1 to 4 days per year in the eastern United States and 4 to 30 days in the western United States. A best estimate of worst-day impact can be obtained using the joint probability of the limited mixing condition associated with a large concentration ratio factor f (persistent meteorological conditions). In this analysis we have assumed that this joint frequency can be approximated by the product of the probability of the limited mixing condition itself and the probability of a large concentration ratio. Thus, the worst-day's impact in the eastern United States is best estimated using the 50 percentile concentration ratio factor and in the western United States by the 95 percentile factor (exceeded only 5 percent of time). We have also assumed in this study that the concentration ratio factors apply at all downwind distances even though they are based on measurements within 20 km of a power plant, an assumption that should be examined in future measurement and analytical studies.

Thus, based on these different concentration ratio factors, the calculations using conservative EPA screening techniques would yield concentration estimates larger than our best estimates by factors ranging from 1.6 to 8. Our best estimates of worst-day concentrations in the western United States are a factor of 1.6 below those estimated by EPA screening techniques, and our estimates of worst-day impacts in the eastern United States are a factor of 7 to 8 below the conservative EPA estimates.

The model used to estimate regional air quality impacts and visual range reduction due to several power plants sited throughout a region is described in Chapter IV.

## D. VISIBILITY IMPAIRMENT

The impacts of different rates of power plant $SO_2$ and $NO_x$ emissions on visual range and atmospheric coloration were evaluated using a plume visibility model recently developed for the EPA by SAI (Latimer et al., 1978). The reader is referred, in particular, to Volumes I and III of that report for a complete description of the model and the parameters used to characterize visibility. In this section, we briefly describe the four parameters that have been used to characterize visibility impairment and the assumptions made in the model calculations.

## 1. Parameters That Characterize Visibility Impairment

We used four parameters to characterize visibility impairment caused by power plant plumes:

- Percentage reduction in visual range
- Blue-red ratio
- Plume contrast
- $\Delta E$.

Each is discussed below.

Visual range is defined as the farthest distance at which a black object can be perceived against the clear horizon sky. The percentage reduction in visual range is calculated as follows:

$$\left(1 - \frac{r_v}{r_{v0}}\right) \times 100 \text{ percent} \quad ,$$

where $r_v$ is the visual range for views through the plume center and $r_{v0}$ is the visual range without the plume (ambient background visual range). In most situations, the percentage reduction in visual range is directly proportional to the integral of the plume light scattering and absorption coefficients along the line of sight and is independent of the background visual range. The percentage reduction in visual range is indicative of the "haziness" of objects observed through the plume. Until it is diffused, the plume will affect only a few of the observer's lines of sight; therefore, calculated visual range reduction pertains only to specific lines of sight through the plume center (perpendicular to the plume centerline), not to prevailing visibility. The magnitude of visual range reduction is not necessarily related to the perceptibility of the plume or to atmospheric discoloration. A significant reduction in visual range could occur without a perceptible plume or atmospheric discoloration.

The blue-red ratio indicates the coloration of the plume relative to the unaffected background sky. It is the ratio of the plume light intensity at the blue end of the visible spectrum ($\lambda$ = 0.4 μm) to that at the red end ($\lambda$ = 0.7 μm) divided by the same ratio for the background:

$$R = \frac{I_{\text{plume}}(\text{blue})/I_{\text{back}}(\text{blue})}{I_{\text{plume}}(\text{red})/I_{\text{back}}(\text{red})} \quad .$$

A ratio of 1 indicates that the plume is the same color as the background sky, though not necessarily of the same brightness. Ratios greater than 1 indicate bluish discoloration relative to the background, and ratios of less than 1 indicate yellowish discoloration. If the background sky is blue, the plume could be white or gray with a ratio of less than 1 because the ratio is a relative discoloration index. The plume color will be a more saturated yellow with decreasing values of this ratio (<0.9).

Plume contrast is the normalized difference in light intensity of the plume relative to the background:

$$C_p = \frac{I_p(0.55\ \mu\text{m}) - I_b(0.55\ \mu\text{m})}{I_b(0.55\ \mu\text{m})} \quad .$$

Contrast is evaluated at a wavelength $\lambda$ of 0.55 μm, which is the midpoint of the visible spectrum where the human eye is most sensitive. With no color shifts (that is, with a blue-red ratio = 1), a plume will be visible only if it is sufficiently brighter ($C_p > 0$) or darker ($C_p < 0$) than the background sky. There are no experimental data concerning the perceptibility threshold contrast for plumes. A threshold contrast of 0.02 is used in defining the perceptibility of a dark object against the horizon sky in the calculation of visual range; however, it is likely that the threshold contrast for plumes is greater than 0.02 because, in many cases, the boundary between a plume and the background is not distinct owing to the nature of plume dilution. The use of the blue-red ratio in conjunction with the plume contrast at 0.55 μm is a simple way of characterizing plume color. When R > 1, the plume is more blue than the background; when R < 1, the plume is redder (or more yellow-brown); when R = 1, with $C_p(0.55\ \mu m) > 0$, the plume is a brighter white than the horizon, and with $C_p(0.55\ \mu m) < 0$, the plume is a darker gray.

The final step in the quantification of plume perceptibility is the specification of color differences--differences both in color and brightness. In 1976 the Commission Internationale de l'Eclairage (CIE) adopted two color difference formulae by which the perceived magnitude of color differences can be calculated. Color differences are specified by a parameter ΔE, which is a function of the change in light intensity or value (ΔL*) and the change in chromaticity (Δx,Δy). ΔE can be considered as a distance between two colors in a color space. The color space is defined such that equal distances (ΔE) between any two colors correspond to equally perceived color changes. This suggests that a threshold ($\Delta E_0$) can be found to determine whether a given color change is perceptible.

Since the CIE could not decide between two different proposed formulae for ΔE, both were adopted in 1976 as standard means by which color differences can be specified. These color differences, which are labeled ΔE(L*U*V*) and ΔE(L*a*b*), are calculated by the plume visibility code. We have elected to plot E(L*a*b*). ΔE's greater than 20 indicate a strong discoloration, ΔE's between 5 and 20 represent weak discoloration, and those less than 5 indicate that a plume would probably not be perceptible. It is currently uncertain as to what the thresholds of perceptibility are in terms of values of blue-red ratio, plume contrast, and ΔE.

Figure 1 summarizes these qualitative interpretations of the quantitative specifications of visibility impairment. This figure provides a key to Figures 8 and 9 presented in Chapter III.

### 2. Assumptions Used in the Model Calculations

Visibility impairment was calculated for ambient conditions typical of the western United States for the following reasons:

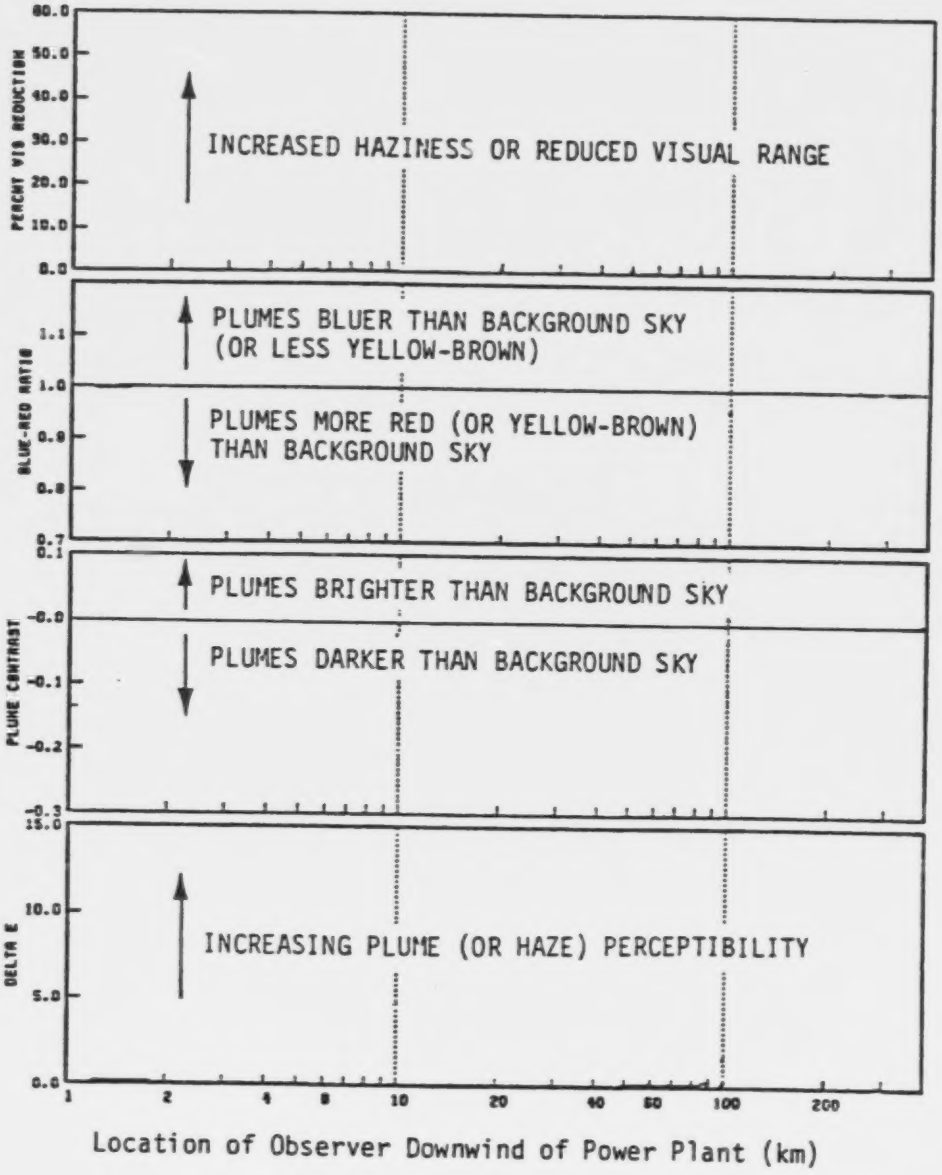


FIGURE 1. KEY TO PARAMETERS USED TO CHARACTERIZE VISIBILITY IMPAIRMENT

- The greatest atmospheric discoloration was found by previous studies (Latimer et al., 1978) to occur in the western United States, where excellent visibility makes plume discoloration easily observable. Indeed, because of the relatively poor background visual range in the eastern United States, plume discoloration would rarely be seen there.
- Calculations of the percentage reduction in visual range caused by power plant plumes based on an assumed background visual range typical of the western United States will be valid for the eastern United States, assuming that all of the plume aerosol flux is within the visual range of the observer (10 to 30 km) and that sulfate formation rates and relative humidity are equal. However, at large downwind distances (>200 km), percentage reductions in visual range calculated for the western United States will overestimate impairment in the eastern United States because some of the plume sulfate will have dispersed beyond the 10 to 30 km background visual range.

The following conditions were assumed in our visibility calculations:

- The observer looks horizontally across the plume at a given downwind distance.
- The sun zenith angle is 45°.
- The scattering angle (between direct solar radiation and the observer's line of sight) is 90°.
- The observer is located 5 km from the plume centerline.
- The background visual range is 130 km.
- The background ozone concentration is 40 ppb.
- The $SO_2$-to-$SO_4^=$ aerosol conversion rate is 0.5 percent per hour.
- The $NO_x$-to-$NO_3^-$ aerosol conversion rate is 0 percent per hour.
- The mixing depth ($H_m$) is 1000 m (for Pasquill C and D stabilities).
- The Pasquill stability categories are C, D, E, and F.
- The surface deposition velocities for gases and aerosols are 1 and 0.1 cm/sec, respectively.

# III IMPACTS OF INDIVIDUAL POWER PLANTS AND THEIR IMPLICATIONS FOR EMISSION CONTROL AND SITING

This chapter discusses the impacts of individual power plants ranging in size from 500 to 3000 Mwe on ambient air quality and visibility. The impacts of alternative $SO_2$ and $NO_x$ emission rates are also described, along with the implications of PSD Regulations and visibility protection for Class I areas, particularly those related to power plant siting and $SO_2$ and $NO_x$ emission control.

## A. IMPACTS ON GROUND-LEVEL AIR QUALITY

The air quality models and meteorological scenarios defined in Chapter II were used to calculate ground-level concentrations as a function of distance downwind of a power plant. Models for plume impingement on elevated terrain and for limited-mixing, light-wind conditions in flat terrain were used for downwind distances $0 < x < 50$ km. For distances $0 < x < 100$ km, models were used to model ground-level concentrations in flat terrain resulting from stable conditions and from moderate-wind, limited-mixing conditions. These calculations were supplemented with long range transport model calculations for distances beyond 100 km downwind. The transport model developed for this study assumes uniform mixing within a 11.25° sector between ground level and 1000 m aloft and reductions in $SO_2$ flux resulting from surface deposition and sulfate formation.

To make tractable the calculation of both 3-hour- and 24-hour-average $SO_2$ concentrations due to emissions from hypothetical power plants of different sizes (Mwe) and $SO_2$ emission rates ($lb/10^6$ Btu), we calculated the peak short-term-average (less than 1 hour) $SO_2$ concentrations $\chi_{peak}$ normalized by $SO_2$ emission rate $Q_o$. Thus, with this normalized $\chi/Q_o$, we can compute 3-hour or 24-hour concentrations using a simple ratio:

$$\chi_{ave} = f_{ave/peak}\, Q_o \left(\frac{\chi_{peak}}{Q_o}\right) \quad . \qquad (8)$$

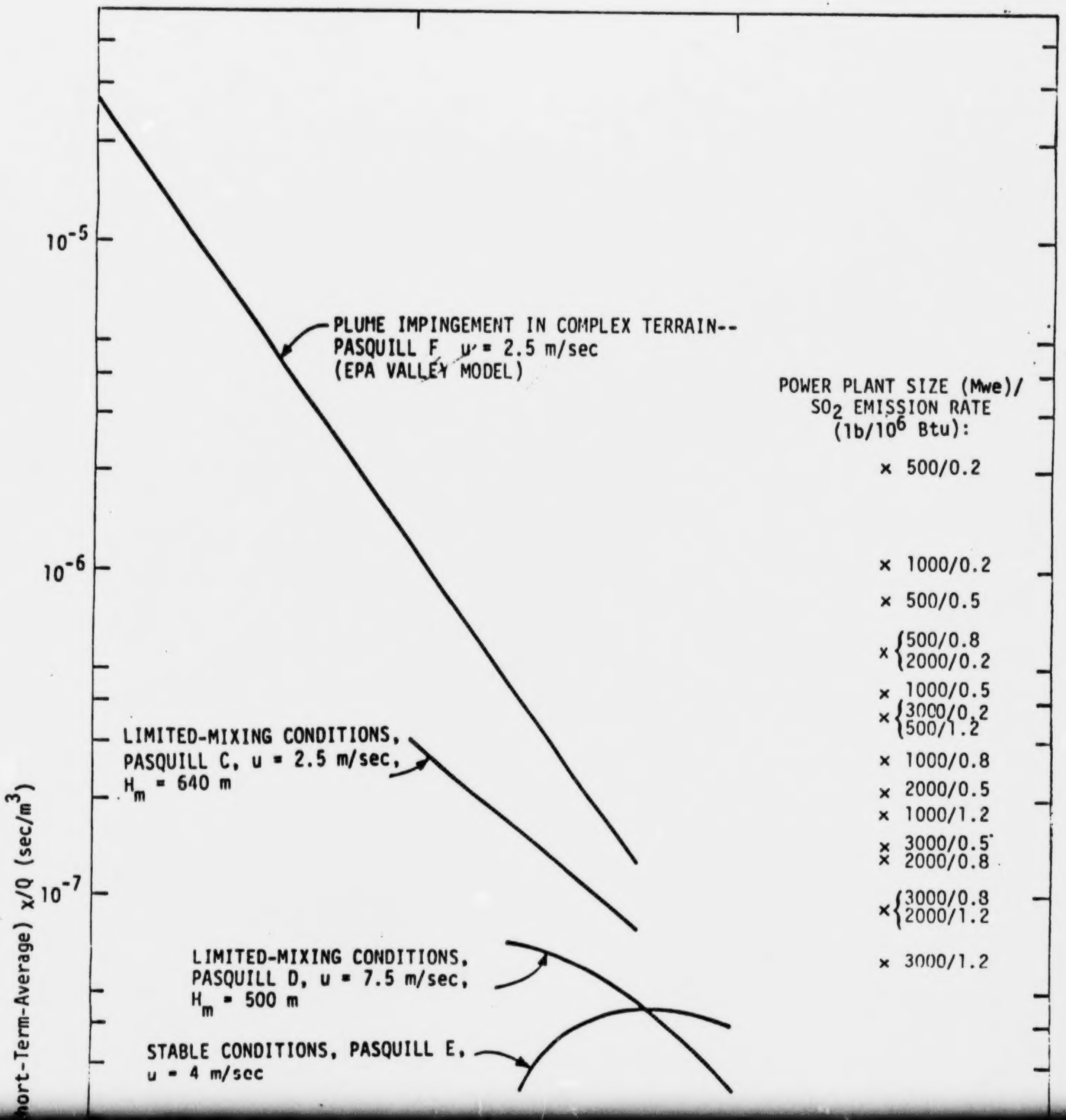
Figure 2 shows these short-term-average $(\chi/Q)$'s as a function of downwind distance and meteorological/atmospheric dispersion condition. Note that the units of $\chi/Q$ are seconds per cubic meter.

We have provided clear plastic overlays so that the procedure for obtaining the ratios described above can be performed graphically by the reader. For this task, select the clear plastic overlay corresponding to the averaging period desired (3 or 24 hour), and align the overlay on the $\chi/Q$ figure by placing the appropriate "x" on the overlay sheet directly on top of the "x" corresponding to the desired power plant size (500, 1000, 2000, or 3000 Mwe) and $SO_2$ emission rate (0.2, 0.5, 0.8, or 1.2 $lb/10^6$ Btu). Note that these plastic overlays show the values of the NAAQS and the Class I, II, and III PSD increments. Thus, the reader can determine the maximum 3-hour- and 24-hour-average $SO_2$ concentrations resulting from power plants of given $SO_2$ emissions and can immediately find out whether the power plant would be in compliance with PSD increments and air quality standards.

## B. IMPLICATIONS OF PSD AND ALTERNATE $SO_2$ EMISSION CONTROLS ON POWER PLANT SITING

The reader can use the graphical technique described above to determine the minimum separation distances between power plants of different size and $SO_2$ emission rate and different PSD areas necessary to meet the 3-hour- and 24-hour-average $SO_2$ PSD increments. We have applied the graphical technique to arrive at the conclusions discussed in the following paragraphs.

The 24-hour-average $SO_2$ PSD increments are more restrictive than the 3-hour-average increments. For example, even in flat terrain a 2000 Mwe plant emitting $SO_2$ at a rate of 0.5 $lb/10^6$ Btu or a 1000 Mwe plant emitting at a rate of 0.8 $lb/10^6$ Btu would violate the 24-hour-average $SO_2$ PSD Class II increment using the conservative EPA screening models; they would just meet the increment using the best-estimate models. The same plant easily meets the 3-hour Class II increment.


PLUME IMPINGEMENT IN COMPLEX TERRAIN--
PASQUILL F u = 2.5 m/sec
(EPA VALLEY MODEL)
LIMITED-MIXING CONDITIONS,
PASQUILL C, u = 2.5 m/sec,
$H_m$ = 640 m
LIMITED-MIXING CONDITIONS,
PASQUILL D, u = 7.5 m/sec,
$H_m$ = 500 m
STABLE CONDITIONS, PASQUILL E,
u = 4 m/sec
POWER PLANT SIZE (Mwe)/
$SO_2$ EMISSION RATE
($lb/10^6$ Btu):
× 500/0.2
× 1000/0.2
× 500/0.5
× {500/0.8 2000/0.2
× 1000/0.5
× {3000/0.2 500/1.2
× 1000/0.8
× 2000/0.5
× 1000/1.2
× 3000/0.5
× 2000/0.8
× {3000/0.8 2000/1.2
× 3000/1.2
$10^{-5}$
$10^{-6}$
$10^{-7}$
hort-Term-Average) $\chi/Q$ (sec/$m^3$)

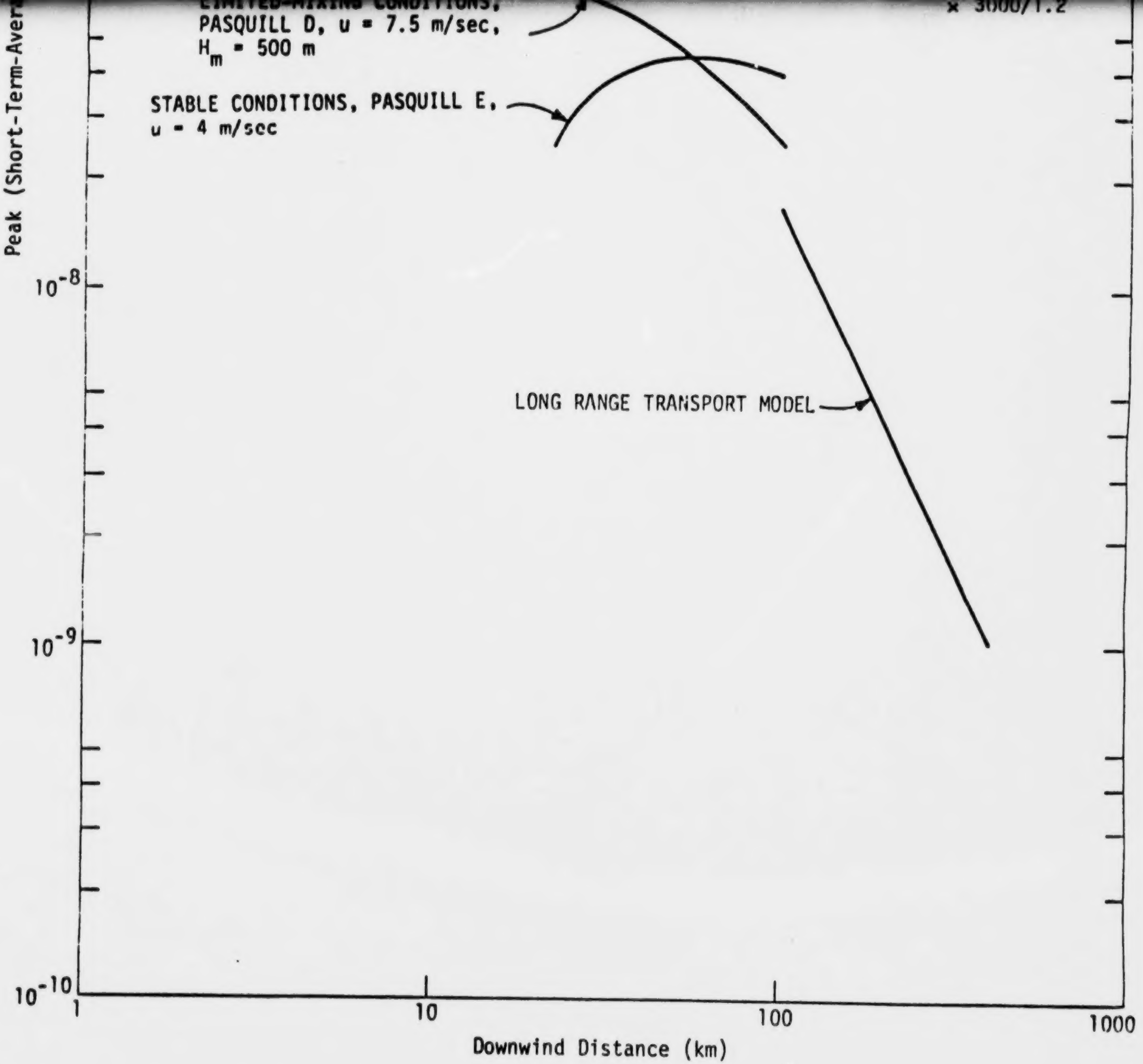
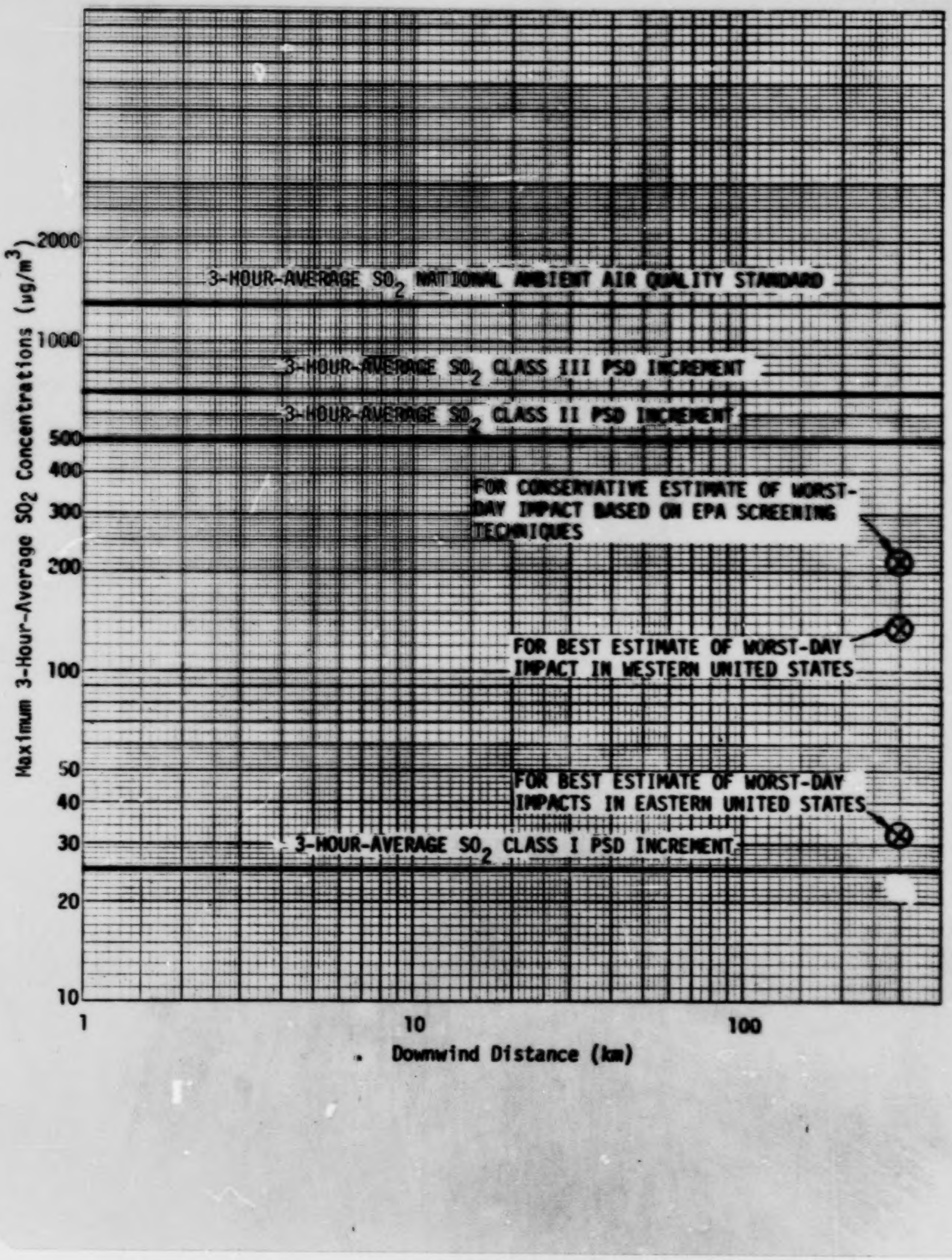
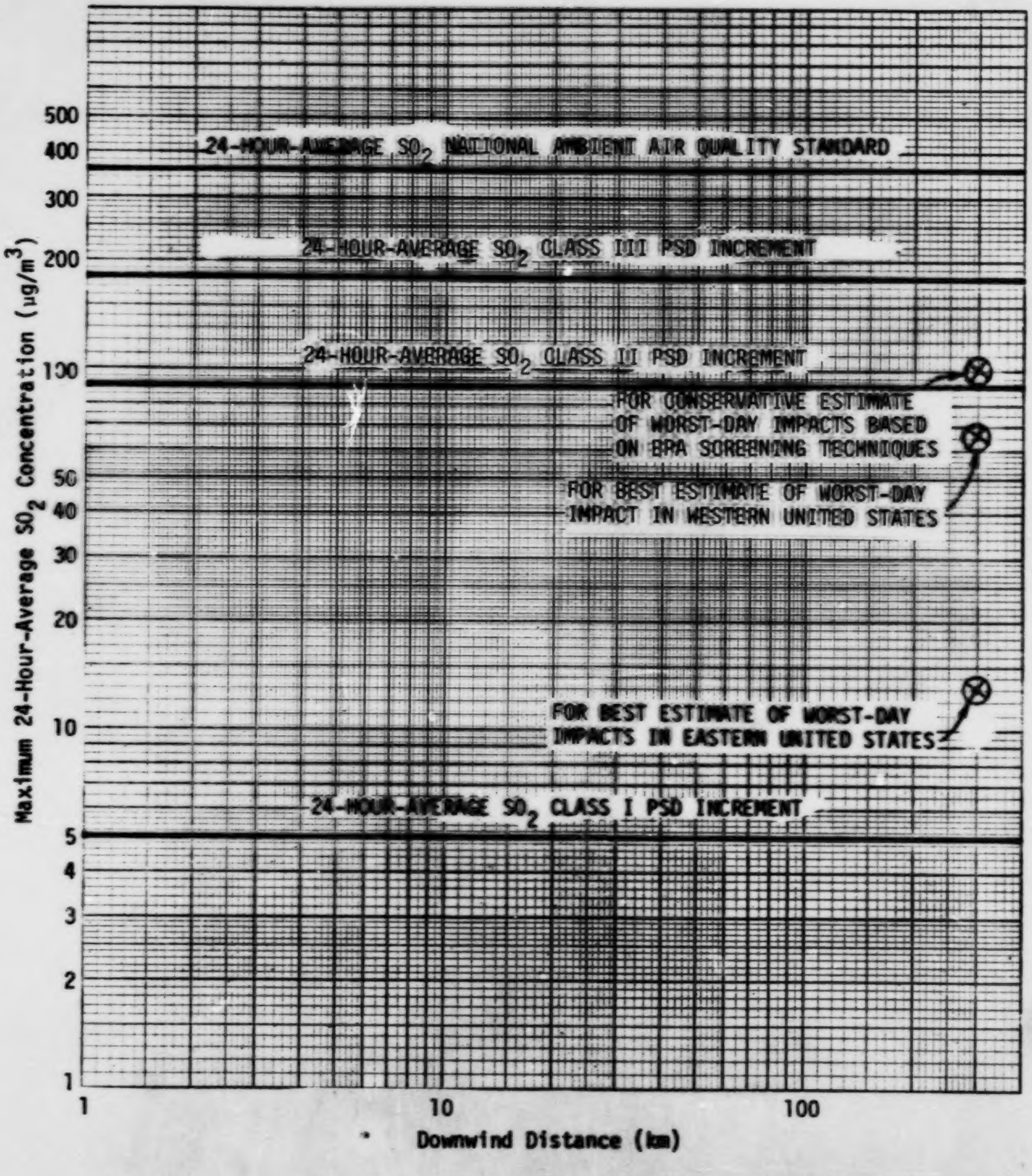


FIGURE 2. MAXIMUM GROUND-LEVEL AIR QUALITY IMPACTS


3-HOUR-AVERAGE $SO_2$ NATIONAL AMBIENT AIR QUALITY STANDARD
3-HOUR-AVERAGE $SO_2$ CLASS III PSD INCREMENT
3-HOUR-AVERAGE $SO_2$ CLASS II PSD INCREMENT
FOR CONSERVATIVE ESTIMATE OF WORST-DAY IMPACT BASED ON EPA SCREENING TECHNIQUES
FOR BEST ESTIMATE OF WORST-DAY IMPACT IN WESTERN UNITED STATES
FOR BEST ESTIMATE OF WORST-DAY IMPACTS IN EASTERN UNITED STATES
3-HOUR-AVERAGE $SO_2$ CLASS I PSD INCREMENT
Maximum 3-Hour-Average $SO_2$ Concentrations ($\mu g/m^3$)
2000
1000
500
400
300
200
100
50
40
30
20
10
1
10
100
Downwind Distance (km)


24-HOUR-AVERAGE $SO_2$ NATIONAL AMBIENT AIR QUALITY STANDARD
24-HOUR-AVERAGE $SO_2$ CLASS III PSD INCREMENT
24-HOUR-AVERAGE $SO_2$ CLASS II PSD INCREMENT
FOR CONSERVATIVE ESTIMATE OF WORST-DAY IMPACTS BASED ON EPA SCREENING TECHNIQUES
FOR BEST ESTIMATE OF WORST-DAY IMPACT IN WESTERN UNITED STATES
FOR BEST ESTIMATE OF WORST-DAY IMPACTS IN EASTERN UNITED STATES
24-HOUR-AVERAGE $SO_2$ CLASS I PSD INCREMENT
Maximum 24-Hour-Average $SO_2$ Concentration ($\mu g/m^3$)
500
400
300
200
100
50
40
30
20
10
5
4
3
2
1
1
10
100
Downwind Distance (km)

We should point out that the minimum separation distance between any of the power plants considered and elevated terrain features in Class I areas is at least 50 km, based on conservative screening analyses using the EPA-recommended Valley Model. However, with Figure 2 the reader can verify that the minimum separation distance between a power plant and a Class I area would be more than 50 km in most cases, simply to prevent exceedances of Class I PSD increments in low-terrain areas.

Figure 3 illustrates the estimated separation distances between power plants and Class I areas based on the conservative EPA screening techniques. Note that with larger $SO_2$ emission rates resulting from less stringent $SO_2$ control the separation distance between a plant site and a Class I area must increase. For example, a well-controlled 2000 Mwe plant burning low-sulfur coal (0.2 lb/$10^6$ Btu) would have to be sited about 100 km from a Class I area to ensure that 24-hour-average $SO_2$ PSD Class I increments were not exceeded, based on conservative screening assumptions. However, the same plant without controls might have to be sited more than 150 km from a Class I area.*

Another constraint on power plant siting that is particularly significant in the western United States derives from the relatively high $SO_2$ concentrations that can occur in elevated terrain areas. As Figure 2 illustrates, if there is elevated terrain near the power plant site equal to or higher than the effective stack height H, the EPA Valley Model calculations predict significantly higher concentrations than would be predicted in low-terrain areas. Figures 4 and 5 illustrate the minimum separation distances between power plants and elevated terrain in Class II and Class III areas, respectively, based on EPA Valley model calculations.

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* It must be emphasized that these constraints on siting, which are based on conservative screening techniques, are likely to be more severe than those encountered in most situations. However, regardless of the assumptions selected for modeling, siting constraints increase with increasing emissions.

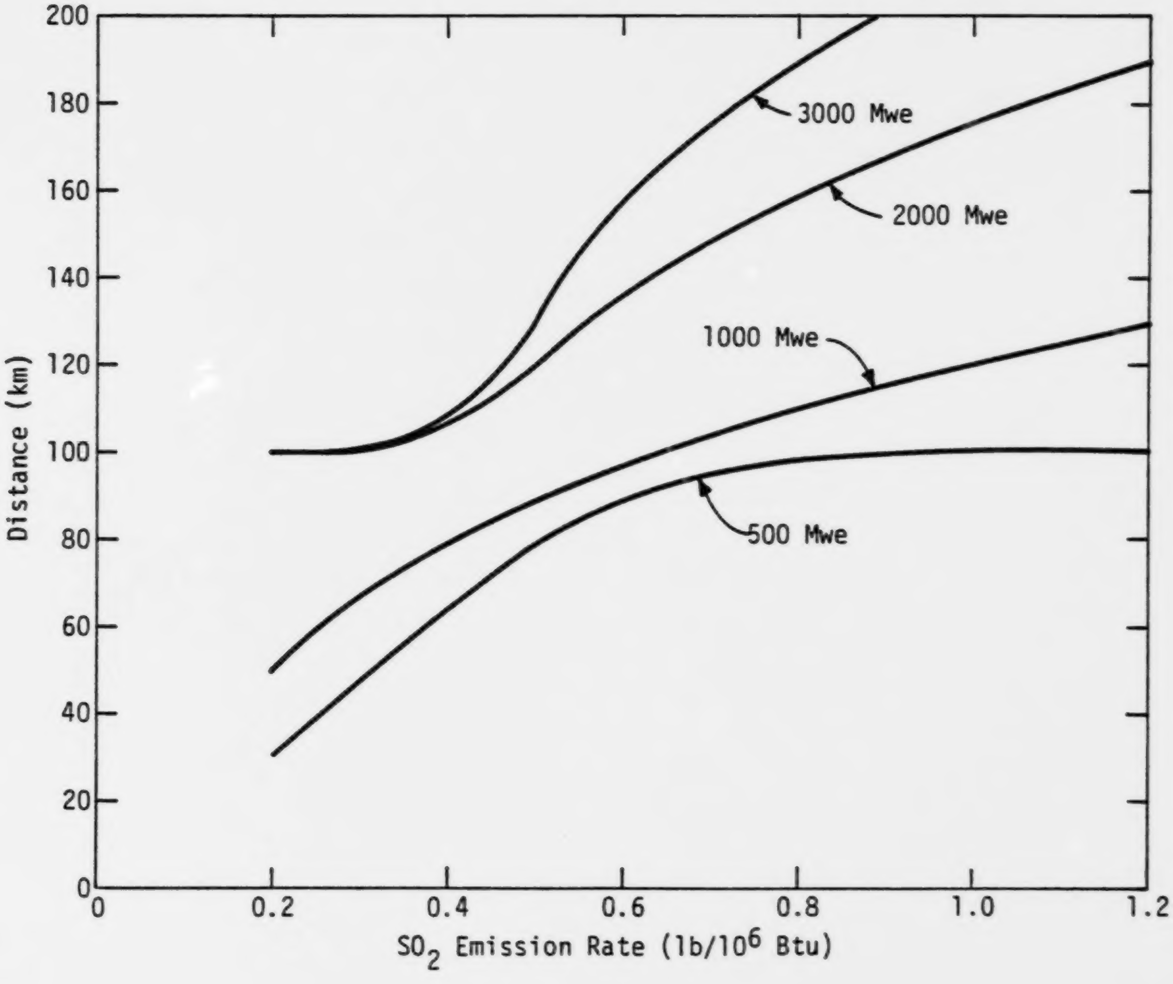


FIGURE 3. ESTIMATED MINIMUM SEPARATION DISTANCES BETWEEN COAL-FIRED POWER PLANTS AND CLASS I AREAS BASED ON CONSERVATIVE SCREENING ANALYSIS TECHNIQUES

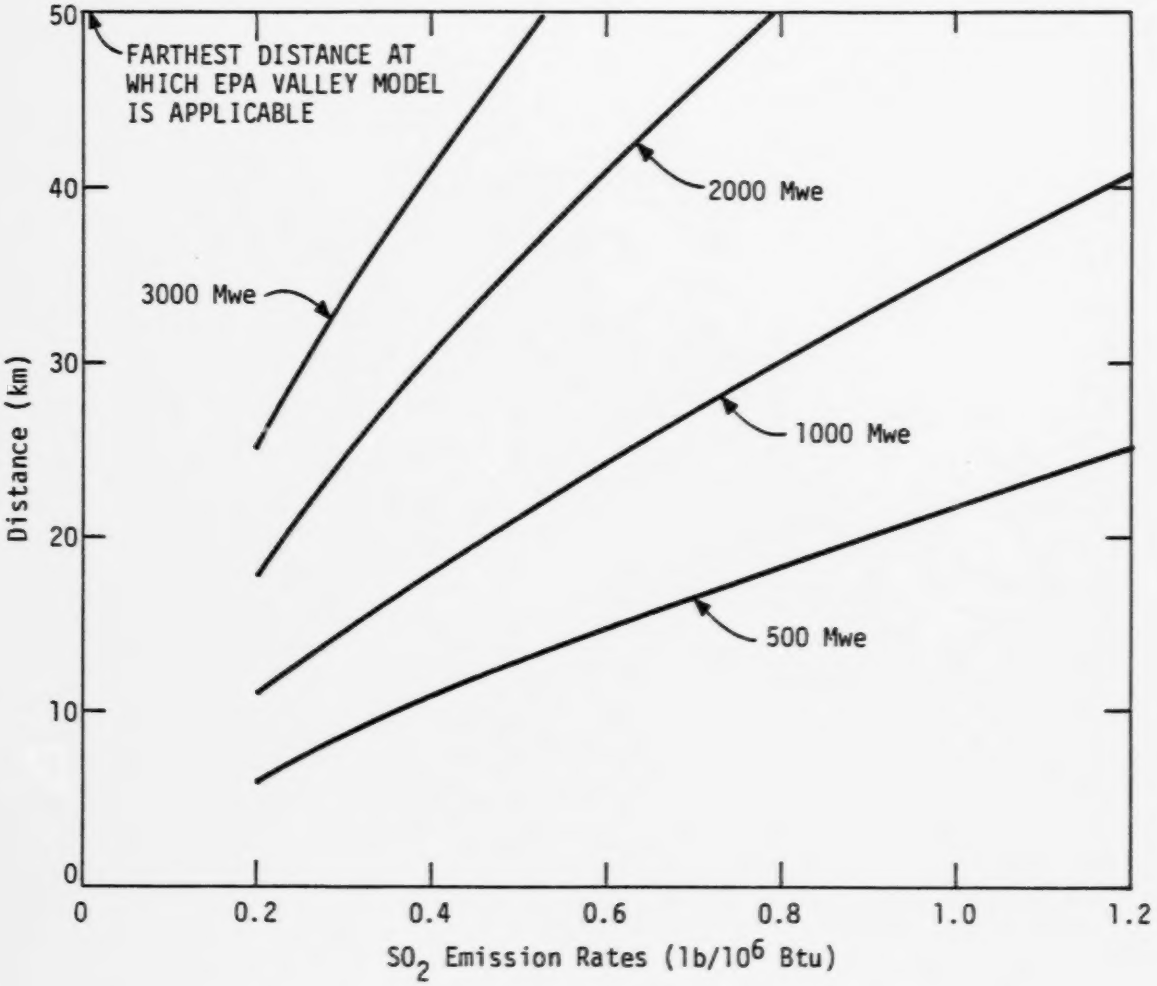


FIGURE 4. MINIMUM SEPARATION DISTANCES BETWEEN COAL-FIRED POWER PLANTS AND ELEVATED TERRAIN IN PSD CLASS II AREAS BASED ON EPA VALLEY MODEL CALCULATIONS

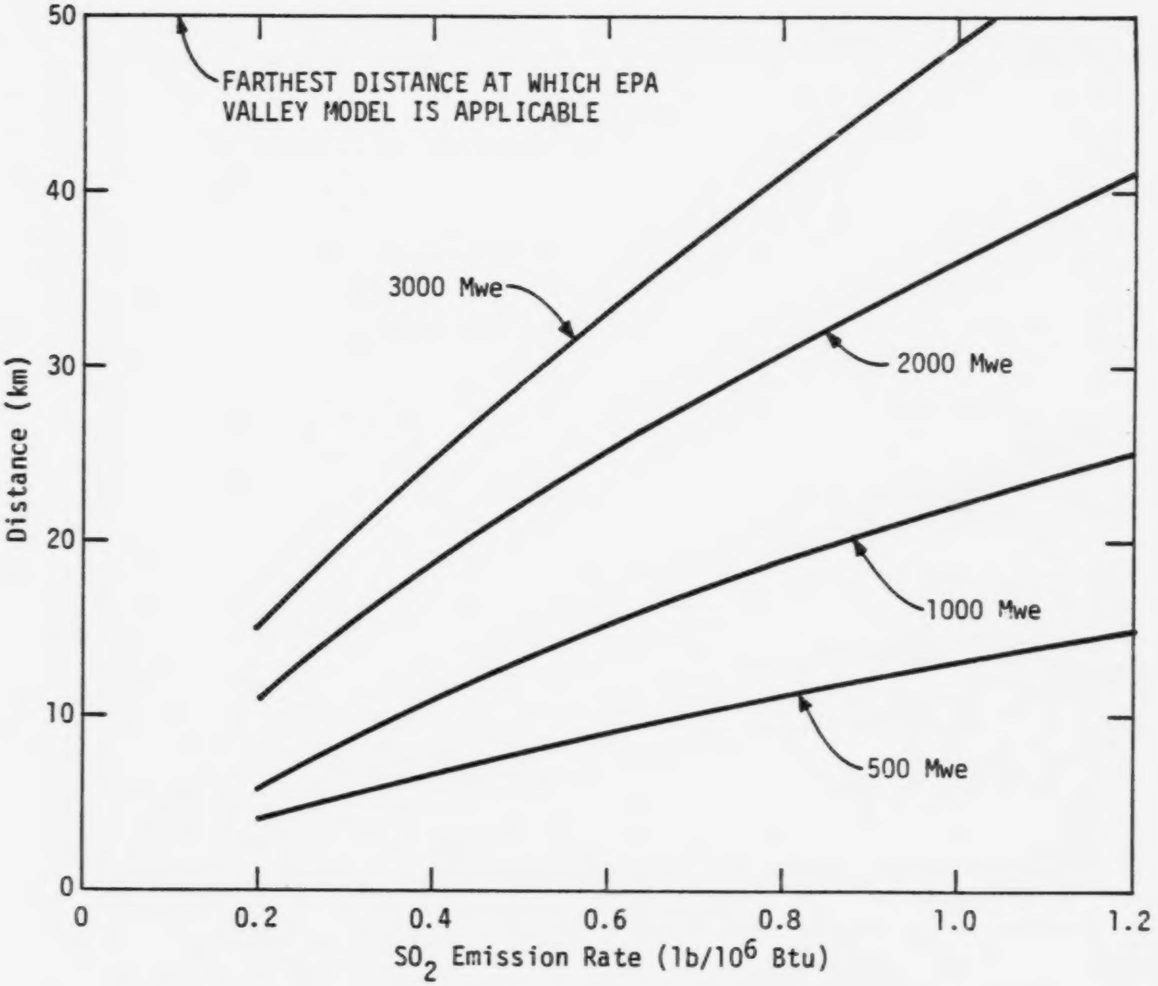


FIGURE 5. MINIMUM SEPARATION DISTANCES BETWEEN COAL-FIRED POWER PLANTS AND ELEVATED TERRAIN IN PSD CLASS III AREAS BASED ON EPA VALLEY MODEL CALCULATIONS

Figure 4 illustrates that a well-controlled 2000 Mwe coal-fired power plant (0.2 lb/$10^6$ Btu) would have to be sited 18 km away from elevated terrain in Class II areas. If the same plant were not as well controlled and its $SO_2$ emissions were greater than 0.8 lb/$10^6$ Btu, the plant would have to be sited more than 50 km from elevated terrain. Since many potential siting areas in the western United States are located in the vicinity of elevated terrain, it would be more difficult to find a suitable site for a power plant emitting more than 0.2 lb/$10^6$ Btu. The many valleys in Nevada, Utah, Colorado, Arizona, and New Mexico have widths ranging from 30 to 50 km and are surrounded by mountains, ridges, or plateaus. With a plant site in the middle of such a valley, elevated terrain would be 15 to 25 km away. Thus, if basic EPA Valley Model calculations are used as the basis for PSD reviews, full $SO_2$ control may be required simply to meet PSD Class II increments in complex terrain.

In summary, with less stringent $SO_2$ control, siting constraints become more severe relative to Class I areas and elevated terrain. Since large portions of the western United States are near either elevated terrain or Class I areas, stringent $SO_2$ control may be necessary, regardless of New Source Performance Standards, to meet PSD Regulations.

## C. VISIBILITY IMPAIRMENT

We applied SAI's plume visibility model to calculate not only visual impacts (reductions in visual range and plume discoloration, contrast, and perceptibility), but also $SO_x$ and $NO_x$ fluxes and concentrations as a function of downwind distance for a variety of meteorological conditions. We selected a range of meteorological conditions for analysis to document the effect of atmospheric stability on:

> Plume centerline $SO_x$ and $NO_x$ concentrations.
> Ground-level $SO_x$ and $NO_x$ concentrations.
> The fraction of $SO_x$ and $NO_x$ flux that is deposited on the ground.

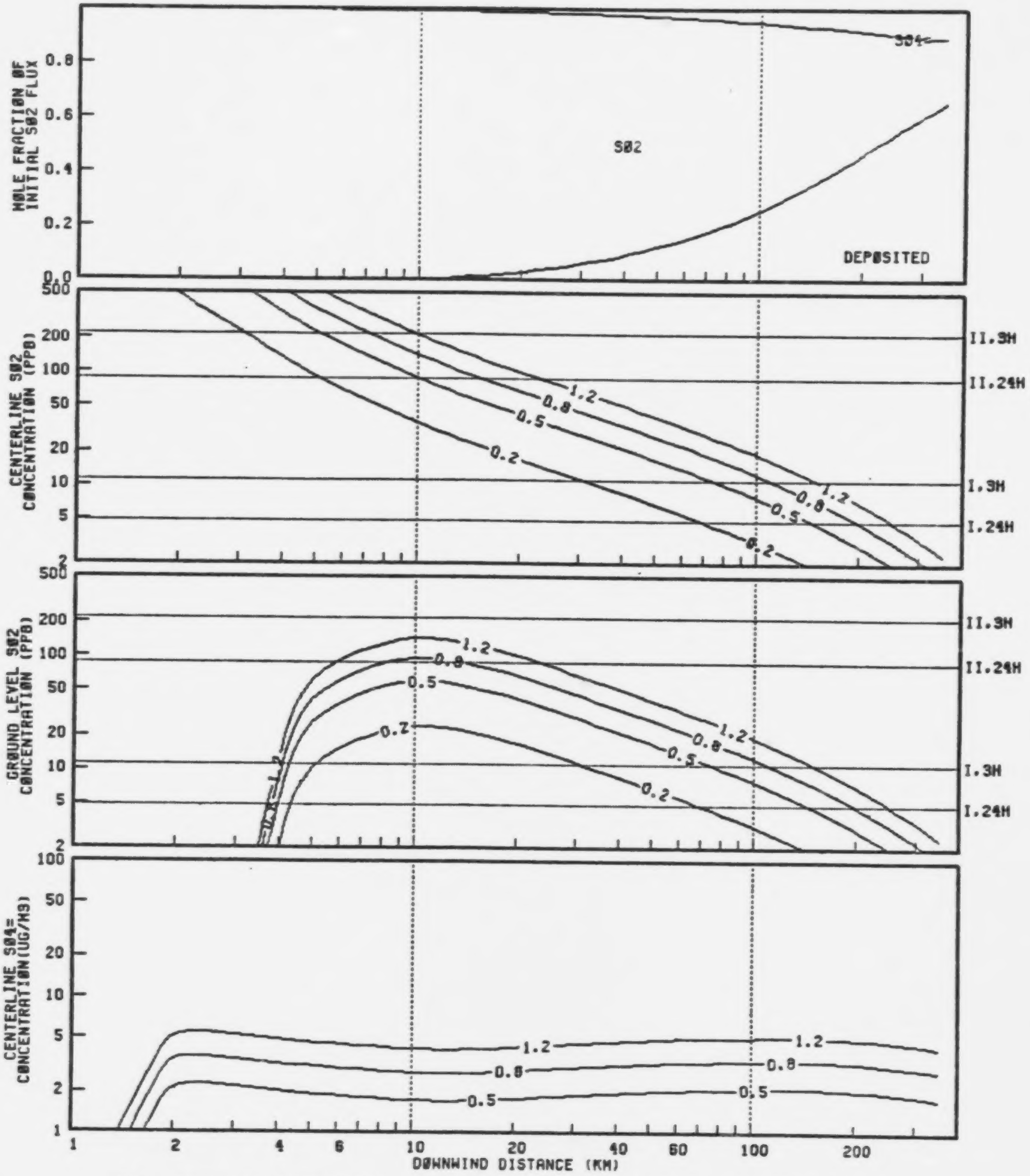
- The fractions of initial $SO_2$ and NO emissions that are converted to sulfate and $NO_2$.
- Visual range.
- Plume coloration, contrast, and perceptibility.

We selected a light, 2.5 m/sec (5.6 mph) wind speed as the basis for the analysis. The impacts during limited-mixing conditions, assuming a 1000 m mixing depth, were analyzed using Pasquill C and D dispersion coefficients, which correspond to slightly unstable and neutral atmospheric conditions. Pasquill D conditions may persist for more than 24 hours, whereas Pasquill C conditions are likely to persist for only 6 to 12 hours (Budney, 1977). The impacts were also analyzed during stable conditions; Pasquill E and F dispersion coefficients were selected, with no vertical limit on mixing. Stable conditions will persist for periods ranging from 11 to 17 hours (Budney, 1977).

A word about the persistence of meteorological conditions is in order here. We can calculate the travel time necessary for a plume parcel to be transported a given distance: Assuming a 2.5 m/sec wind speed, a plume parcel will travel 216 km in 24 hours. Thus, since Pasquill C conditions are expected to persist for 6 to 12 hours, we should consider impacts associated with these conditions out to distances of 50 to 100 km. Similarly, Pasquill E or F conditions persisting 11 to 17 hours will carry emissions to distances of 100 to 150 km. Thus, only the Pasquill D conditions should be used to evaluate impacts beyond 100 to 150 km from a power plant for the assumed 2.5 m/sec wind speed. As pointed out by Holzworth (1972), in many regions of the continental United States, limited mixing conditions with mixing depths ranging from 1000 to 2000 m, persisting for periods of two to five days without precipitation, occur more than once per year.

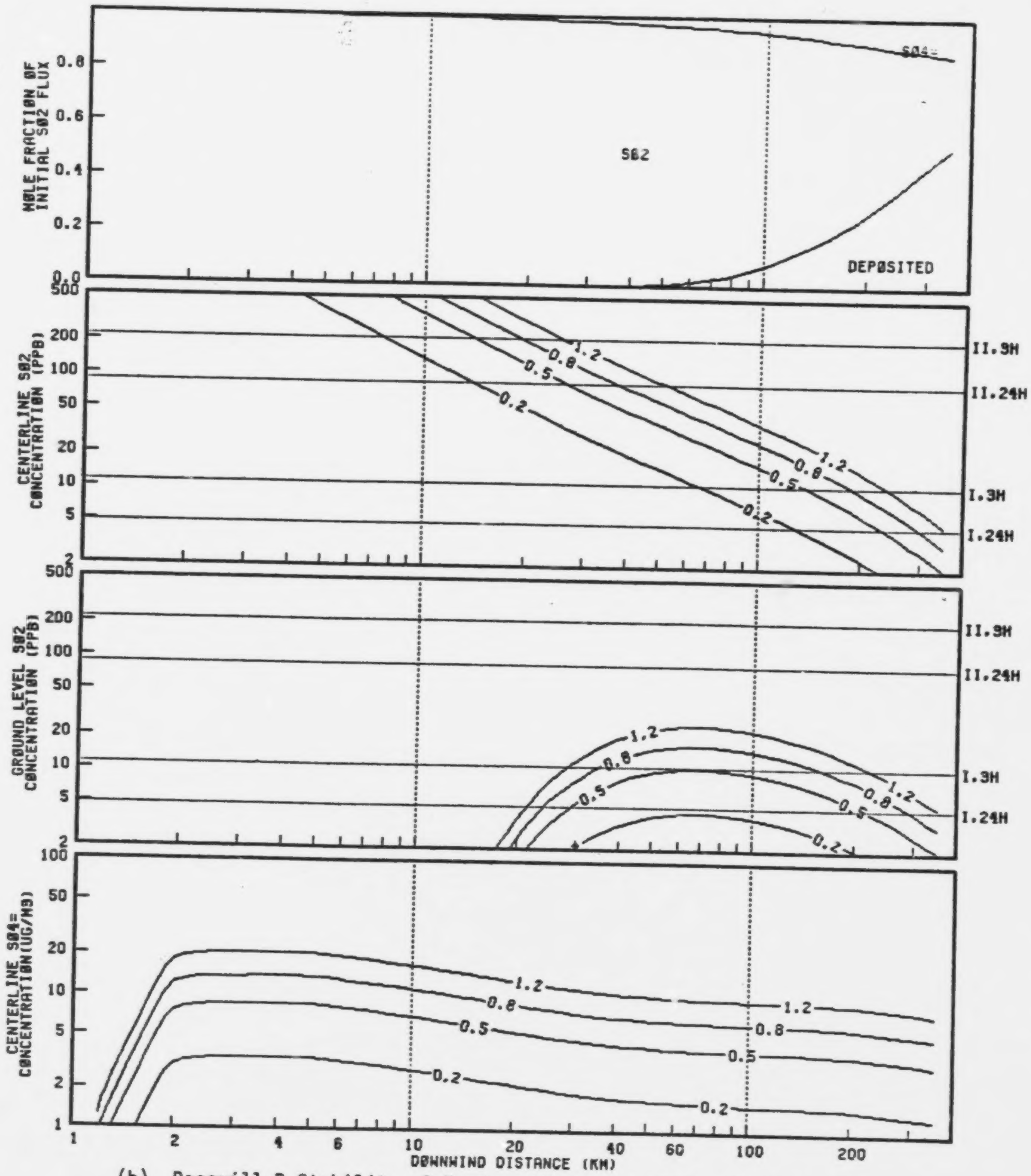
### 1. Effect of $SO_2$ Emission Rates on $SO_x$ Fluxes and Concentrations

Figures 6(a) through 6(d) show for Pasquill C, D, E, and F stability conditions, respectively, the effect of $SO_2$ emission rates on $SO_x$ fluxes



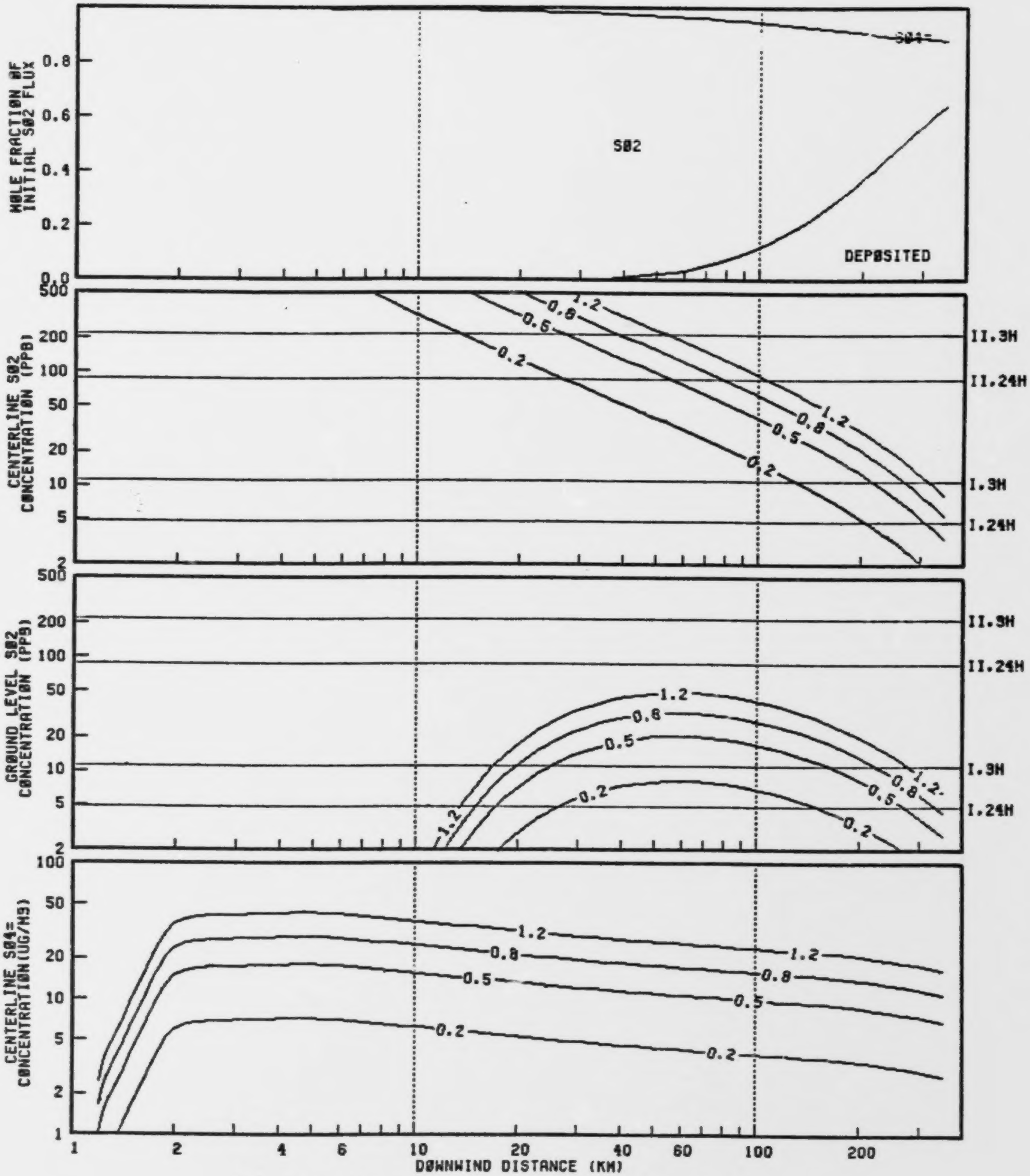
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE 6. EFFECT OF $SO_2$ EMISSION RATES ON $SO_x$ FLUXES AND CONCENTRATIONS DOWNWIND OF A 2000 Mwe COAL-FIRED POWER PLANT. $SO_2$ emission rates in pounds per million Btu are indicated.



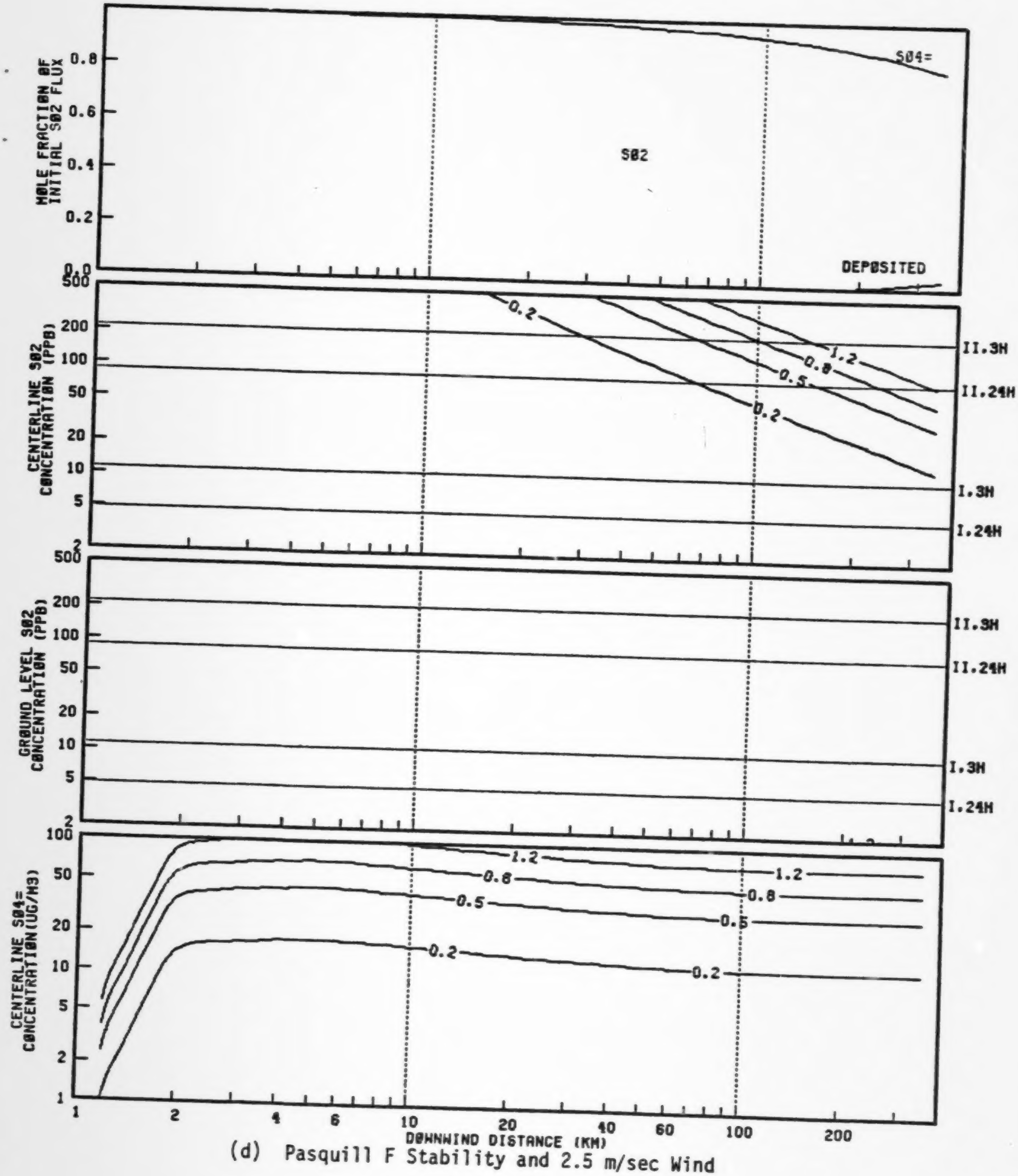
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE 6 (Continued)



(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE 6 (Continued)



(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE 6 (Concluded)

and concentrations as a function of distance downwind from a 2000 Mwe power plant. (Similar plots for 500, 1000, and 3000 Mwe plants are presented in Appendices A, B, and C.)

The top plot in each of these figures shows the distribution of sulfur between $SO_2$ and sulfate in the atmosphere and the amount deposited on the ground as a function of downwind distance. From these plots, one can see that the $SO_2$ flux at large downwind distances decreases as a result of sulfate ($SO_4^=$) formation and surface deposition. (Note that the $SO_4^=$ and $SO_2$ fluxes and the fraction deposited on the ground are represented by the areas above, between, and below the curves in this plot.) Within 100 km of the power plant, only a small fraction of the initial $SO_2$ emissions is converted to sulfate or is deposited. However, at distances of 200 to 350 km downwind, 15 to 20 percent of the initial sulfur flux (power plant emissions) has been converted to sulfate, and up to 65 percent has been deposited. Note that surface deposition is a function of stability because it is linearly proportional to ground-level concentrations; thus, during the stable Pasquill F conditions [Figure 6(d)], surface deposition is negligible because the plume has not mixed to the ground.

The second and third plots in Figures 6(a) through 6(d) show the short-term-average centerline and ground-level $SO_2$ concentrations on log-log plots. For reference, the Class I and Class II 3-hour- and 24-hour-average $SO_2$ PSD increments are indicated by the horizontal lines. These are equivalent short-term-average standards obtained by dividing the 3-hour- and 24-hour-average PSD increments by the conservative average concentration ratio factors recommended by the EPA (Budney, 1977) for screening analyses of 0.9 for 3-hour-average and 0.4 for 24-hour-average concentrations, respectively:

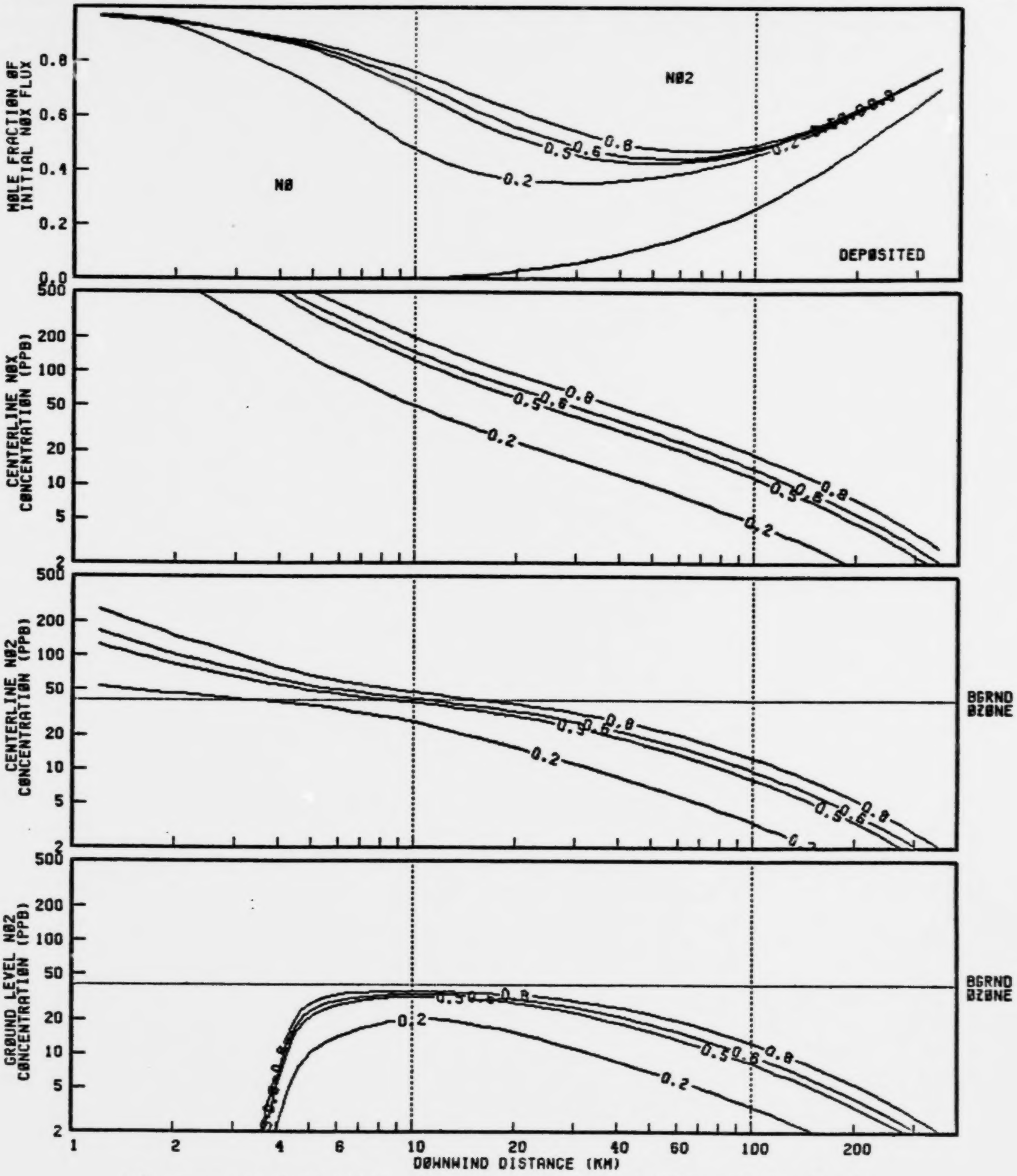
$$\chi_{\text{PSD-peak}} = \frac{\chi_{\text{PSD-ave}}}{f_{\text{ave/peak}}} \quad . \tag{9}$$

The centerline concentrations can also be interpreted as a conservative estimate of maximum ground-level concentrations if plume impingement on elevated terrain were to occur. The ground-level concentrations displayed in the third plot were calculated assuming level terrain (or constant plume elevation above ground). From these plots, one can see that maximum centerline concentrations occur during stable, Pasquill F conditions, whereas maximum ground-level concentrations occur with unstable, limited-mixing, Pasquill C conditions at about 10 km downwind. Note that for limited-mixing conditions (Pasquill C), the plume has become well mixed between the ground and the stable capping layer at 1000 m, so that at distances beyond 20 km the centerline and ground-level concentrations are equal. Under Pasquill C limited-mixing conditions, a 2000 Mwe power plant emitting 0.8 lb $SO_2/10^6$ Btu would barely meet the Class II 24-hour-average $SO_2$ PSD increment at 10 km downwind, based on the conservative, screening type of analysis. Even a well-controlled (0.2 lb/$10^6$ Btu) 2000 Mwe plant would have to be located at least 100 km from a Class I area to meet Class I PSD increments during both limited-mixing and stable conditions. (See the appendices for information on 500, 1000, 3000 Mwe plants.)

The fourth plot in Figures 6(a) through 6(d) shows plume centerline sulfate ($SO_4^=$) concentrations assuming a 0.5 percent per hour $SO_2$-to-$SO_4^=$ conversion rate. Note that for all the meteorological conditions investigated the sulfate concentration remains nearly constant with downwind distance, since sulfate is forming as rapidly as the plume is diluting. Calculated centerline $SO_4^=$ concentrations depend on the $SO_2$ emission rate and the stability. At the 0.2 lb/$10^6$ Btu emission rate, centerline sulfate concentrations range from 1 to 15 μg/$m^3$. For Pasquill C and D, at large downwind distances, ground-level $SO_4^=$ concentrations will equal centerline concentrations because emissions are well mixed. Thus, we see that ground-level sulfate concentrations can be as high as 1, 3, 5, and 8 μg/$m^3$ for the $SO_2$ emission rates of 0.2, 0.5, 0.8, and 1.2 lb/$10^6$ Btu, respectively, from a 2000 Mwe power plant.

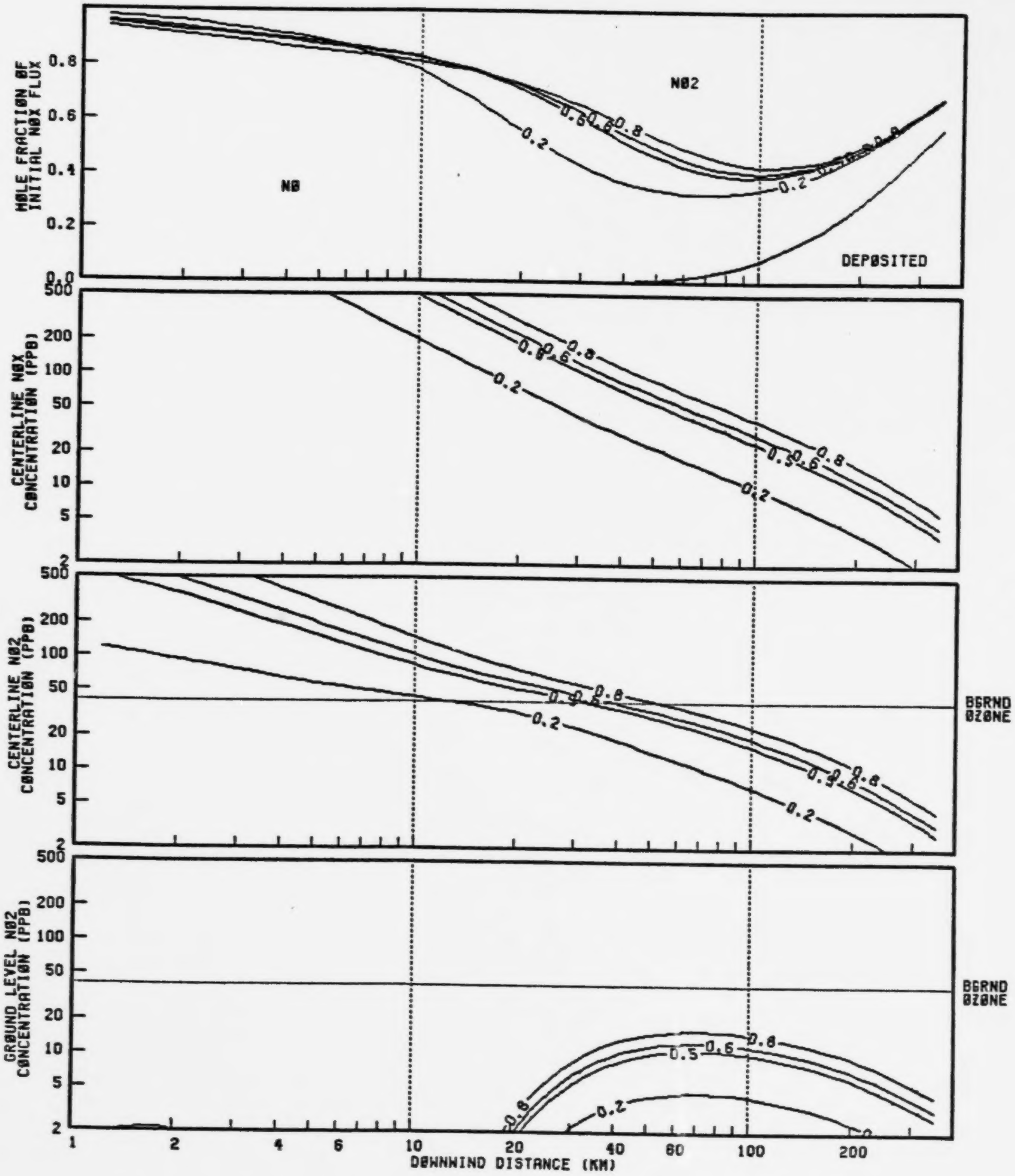
## 2. Effect of $NO_x$ Emission Rates on $NO_x$ Fluxes and Concentrations

Figures 7(a) through 7(d) show plots of $NO_x$ fluxes and concentrations as a function of $NO_x$ emission rates of 0.2, 0.5, 0.6, and 0.8 lb/$10^6$ Btu. Note that the NO-to-$NO_2$ conversion rate, as evidenced by the top plot in each of these figures, depends on the rate of plume dilution (atmospheric



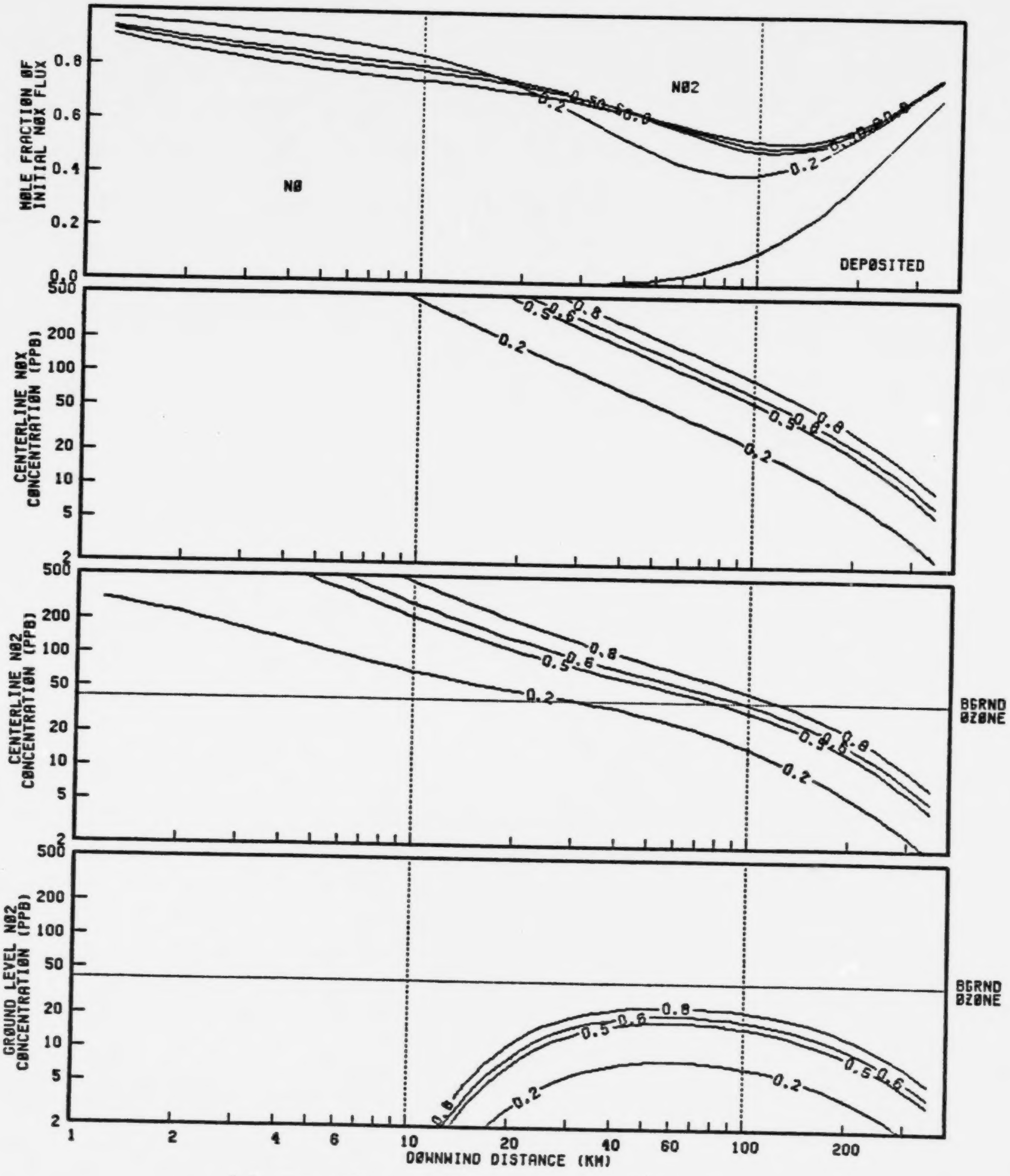
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE 7. EFFECT OF $NO_x$ EMISSION RATES ON $NO_x$ FLUXES AND CONCENTRATIONS DOWNWIND OF A 2000 Mwe COAL-FIRED POWER PLANT. $NO_x$ emissions rates in pounds per million Btu are indicated.



(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE 7 (Continued)



(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE 7 (Continued)

stability). Figure 7(a) shows the limiting effect of the background ozone concentration (assumed to be 40 ppb) on ground-level $NO_2$ concentrations. Both of these effects occur because the reaction responsible for most of the $NO_2$ formation requires background ozone to be mixed into the plume:

$$NO + O_3 \rightarrow NO_2 + O_2 \quad . \tag{10}$$

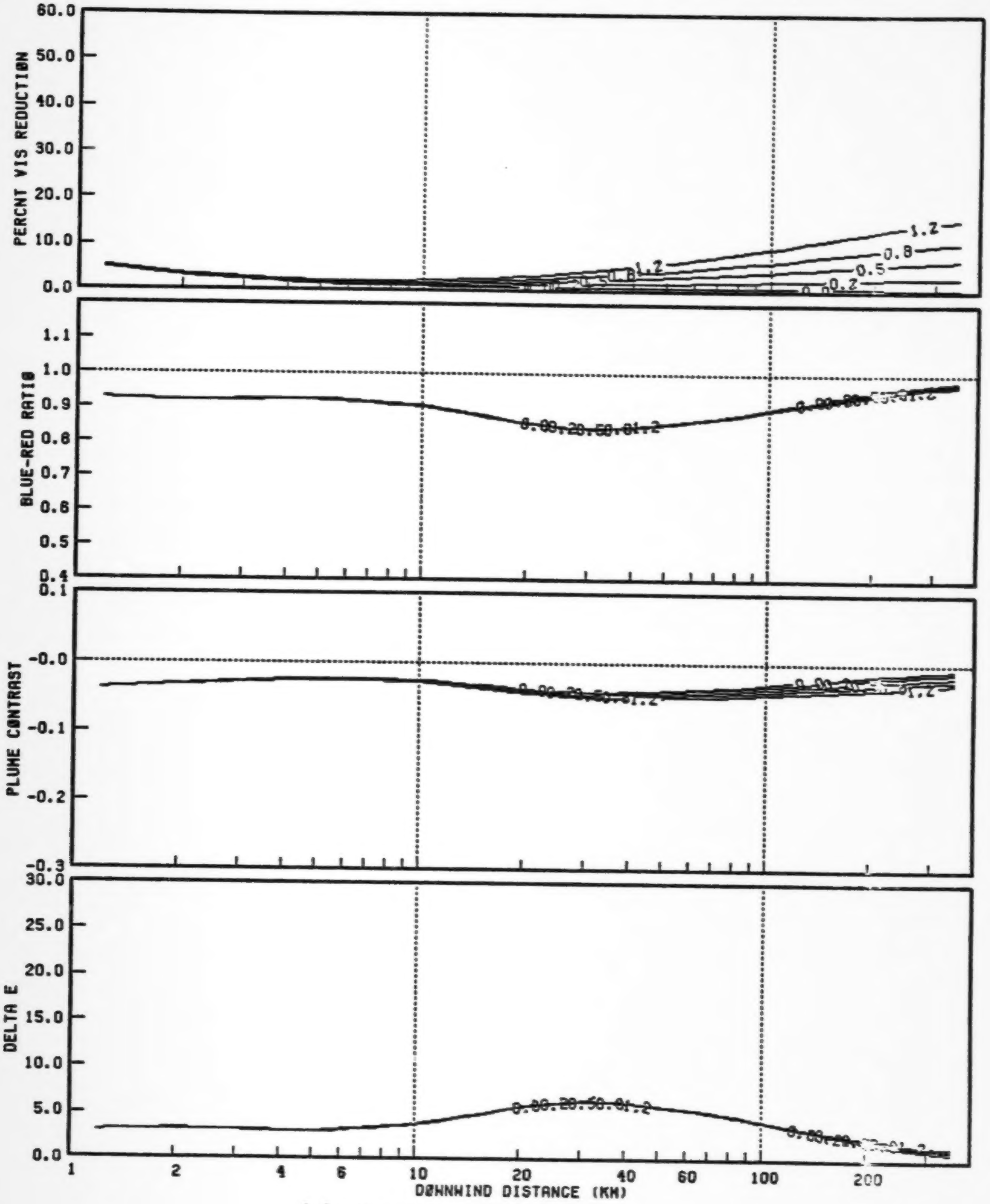
Plots similar to Figures 7(a) through 7(d) are shown in the appendices for other power plant sizes (500, 1000, and 3000 Mwe).

### 3. Effect of $SO_2$ Emission Rates on Visibility Impairment

Keeping the $NO_x$ emission rate fixed at 0.6 $lb/10^6$ Btu, we evaluated the effect of various $SO_2$ emission rates (0, 0.2, 0.5, 0.8, and 1.2 $lb/10^6$ Btu) on visibility impairment. Figures 8(a) through 8(d) show the calculated impairment due to a 2000 Mwe power plant for the four meteorological conditions: Pasquill C and D limited-mixing conditions and Pasquill E and F stable conditions.

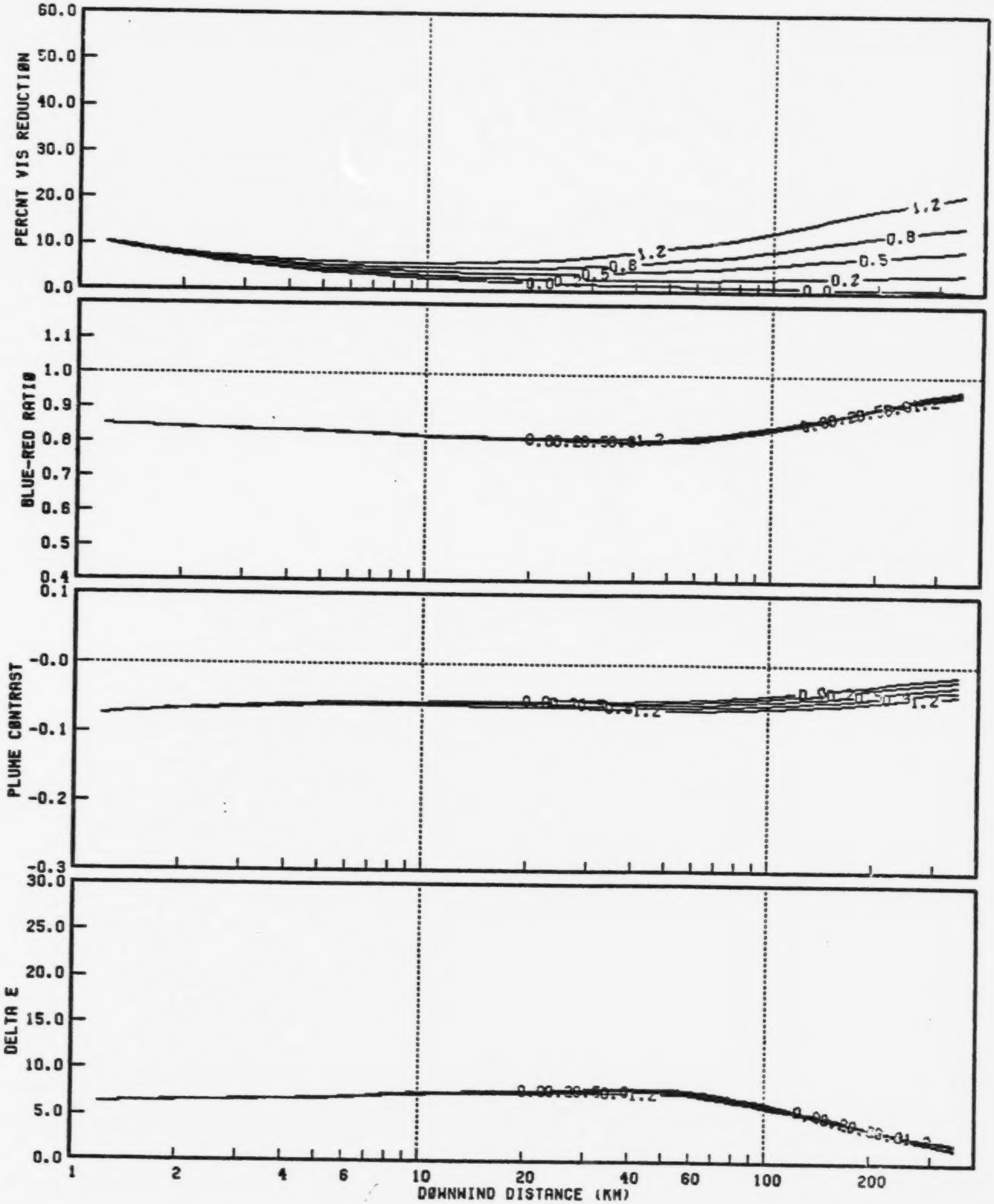
The most striking effect of less stringent $SO_2$ control (increased $SO_2$ emission rates) is the reduction in visual range at distances more than 100 km downwind. As we noted previously, it is appropriate to consider only the Pasquill D meteorological conditions for distances beyond 100 to 150 km. Therefore, from Figure 8(b) we see that at 200 km downwind (approximately one day's plume travel time) the reduction in visual range is 1, 3, 8, 12, and 18 percent for the $SO_2$ emission rates of 0, 0.2, 0.5, 0.8, and 1.2 $lb/10^6$ Btu, respectively. At 350 km downwind, the visual range reduction is 0, 4, 9, 14, and 21 percent, respectively. These values are based on the assumptions that the background visual range is 130 km (typical for nonurban areas of the western United States) and that the observer is viewing with a line of sight perpendicular to the plume axis.

Greater reductions in visual range would be detected if the observer looked along the plume. We used the incremental increases of sulfate concentrations in the plume calculated previously of 1, 3, 5, and 8 $\mu g/m^3$, corresponding to $SO_2$ emission rates of 0.2, 0.5, 0.8, and 1.2 $lb/10^6$ Btu,



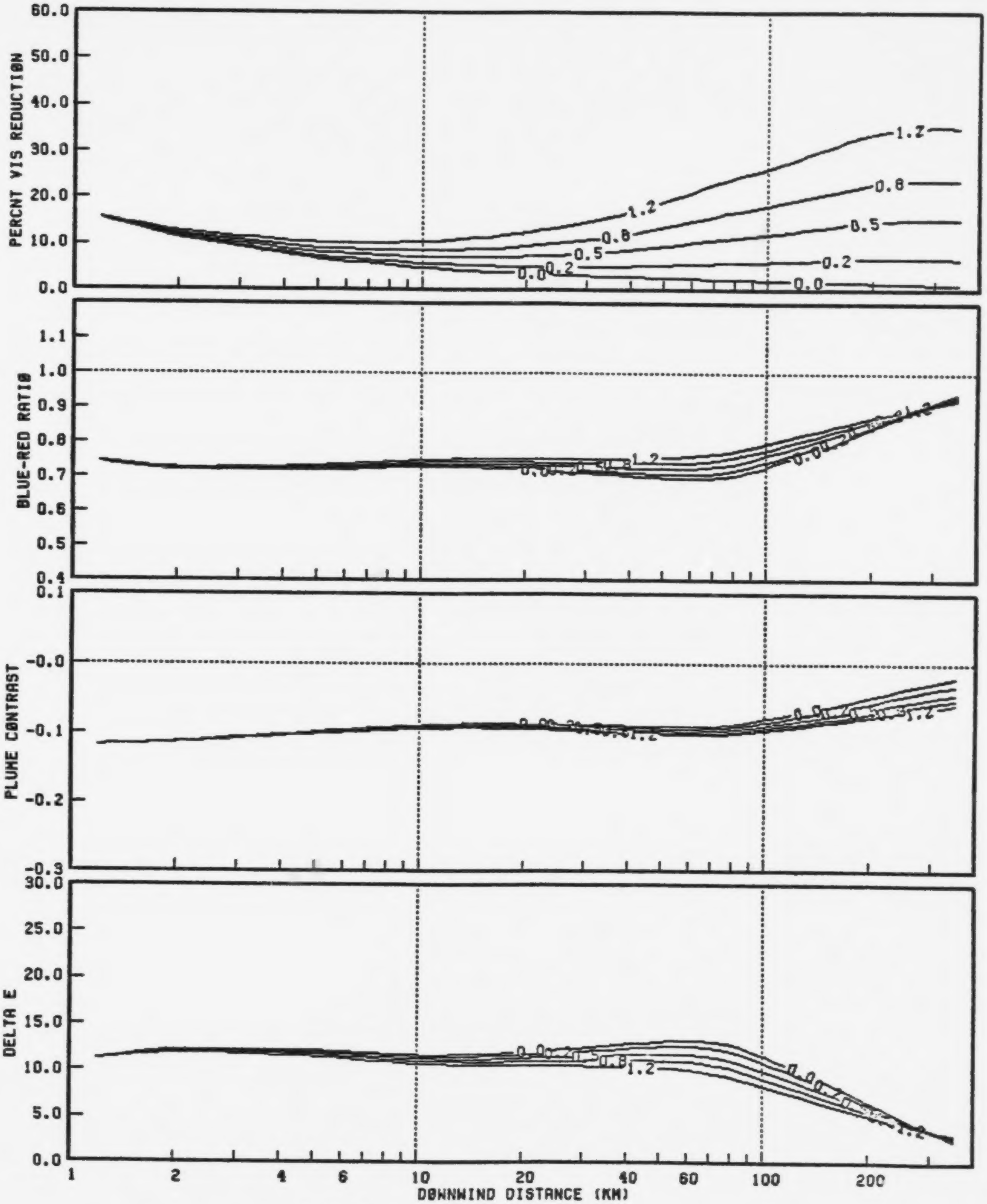
(a) Pasquill Stability C

FIGURE 8. EFFECT OF $SO_2$ EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 2000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. $SO_2$ emission rates in pounds per million Btu are indicated.



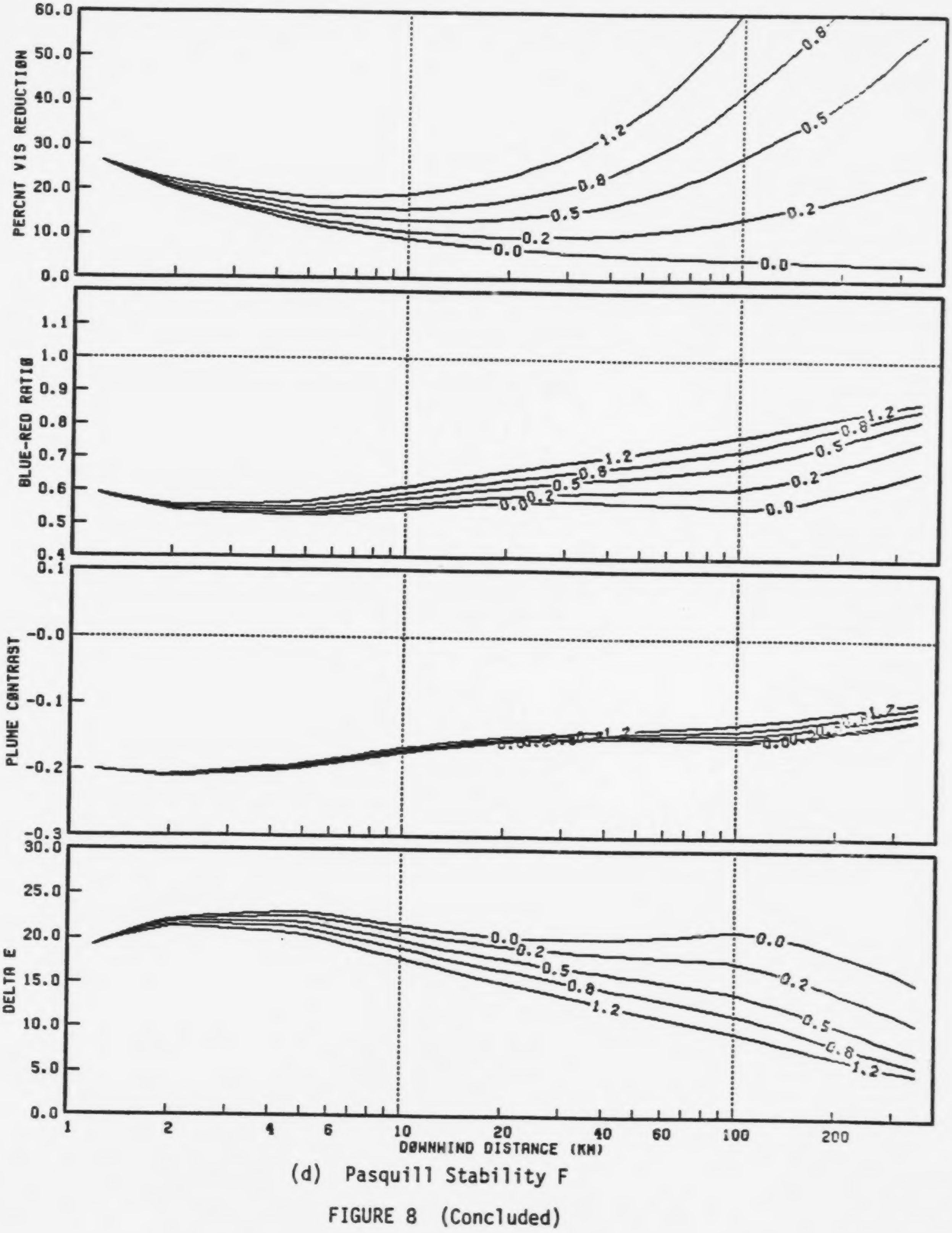
(b) Pasquill Stability D

FIGURE 8 (Continued)



(c) Pasquill Stability E

FIGURE 8 (Continued)



(d) Pasquill Stability F

FIGURE 8 (Concluded)

respectively, from a 2000 Mwe power plant to calculate the maximum reductions in visual range when viewing along the plume. With a background visual range typical of the western United States (130 km), the visual range would be reduced 11, 28, 40, and 51 percent, respectively. For a background visual range typical of the eastern United States (15 km), the visual range would be reduced 2, 4, 7, and 11 percent, respectively. Thus, greater incremental impacts will result from the same sulfate fluxes in the western United States, where the visual range is excellent, than will occur in the eastern United States.

Visual range reduction will be greater in stable, ribbon-like plumes, but these plumes affect only a few lines of sight and do not affect prevailing visibility (in many different directions). Visual impacts caused by stable plumes are better characterized by the appearance of dark, yellow-brown haze, which can be quantified using blue-red ratios, plume contrast, and $\Delta E$.

Thus, if a 2000 Mwe plant located in the western United States burns low-sulfur coal with 85 percent $SO_2$ control, a 4 to 11 percent reduction in visual range, during worst-case meteorological conditions, will occur 200 to 400 km downwind. During typical meteorological conditions, this impact is likely to drop by a factor of 5, producing impacts of 1 to 2 percent. However, without $SO_2$ control, sulfate concentrations would cause a 20 to 50 percent reduction in visual range during poor dispersion conditions and a 5 to 10 percent reduction during typical dispersion conditions.

Another striking observation can be made from Figures 8(a) through 8(d): Increased $SO_2$ emissions cause a decrease in plume coloration, contrast, and perceptibility during stable atmospheric conditions. As shown previously (Latimer et al., 1978), plume $NO_2$ is the principal cause of the dark, yellow-brown discoloration caused by plumes when viewed against a cloudless horizon sky. Increases in the ratio of sulfate to $NO_2$ concentration under these viewing conditions have the effect of masking the yellow-brown coloration with a white-gray haze caused by light scattered by sulfate aerosol. Thus, we see from Figures 8(c) and 8(d) that as $SO_2$ emission rates increase:

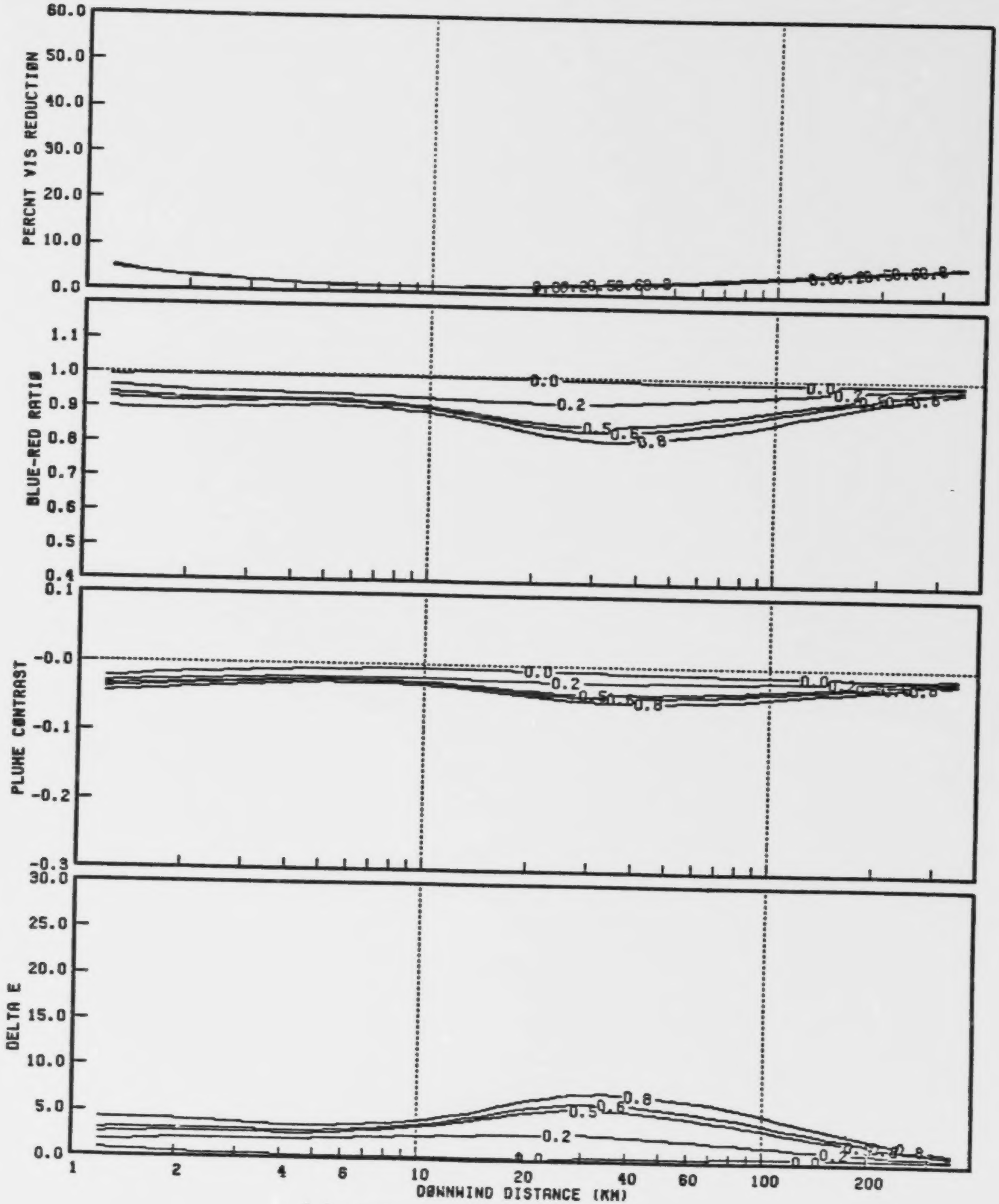
> The plume's yellow-brown coloration is diminished (indicated by blue-red ratios closer to 1).
> The plume becomes less dark (indicated by plume contrasts closer to 0).
> The plume becomes less perceptible (indicated by $\Delta E$'s closer to 0).

The conditions under which plume discoloration would be observed downwind of a power plant were indicated in previous reports (Latimer et al., 1978, Volume III) and in Figures 8(a) through 8(d). Plume discoloration is not likely to be visible in areas where the background visual range is relatively poor, such as the eastern United States. Plume discoloration is most pronounced in areas with good visibility, such as the western United States. Figures 8(a) through 8(d) indicate that meteorological conditions have a strong effect on plume discoloration. During well-mixed conditions [see Figures 8(a) and (b)], plumes would be barely visible ($\Delta E < 10$) assuming a light, 2.5 m/sec wind but would be invisible ($\Delta E < 5$) during well-ventilated conditions with deeper mixed layers and stronger winds than those assumed here. However, during stable, light-wind conditions [as evidenced by Figures 8(c) and 8(d)], yellow-brown plumes ($10 < E < 25$) would be visible as far as 100 to 150 km downwind (assuming that stable, light-wind conditions persist long enough).

As noted previously, $SO_2$ emission control will increase yellow-brown plume coloration, not reduce it. As we show in the next section, $NO_x$ control is necessary to ameliorate plume discoloration.

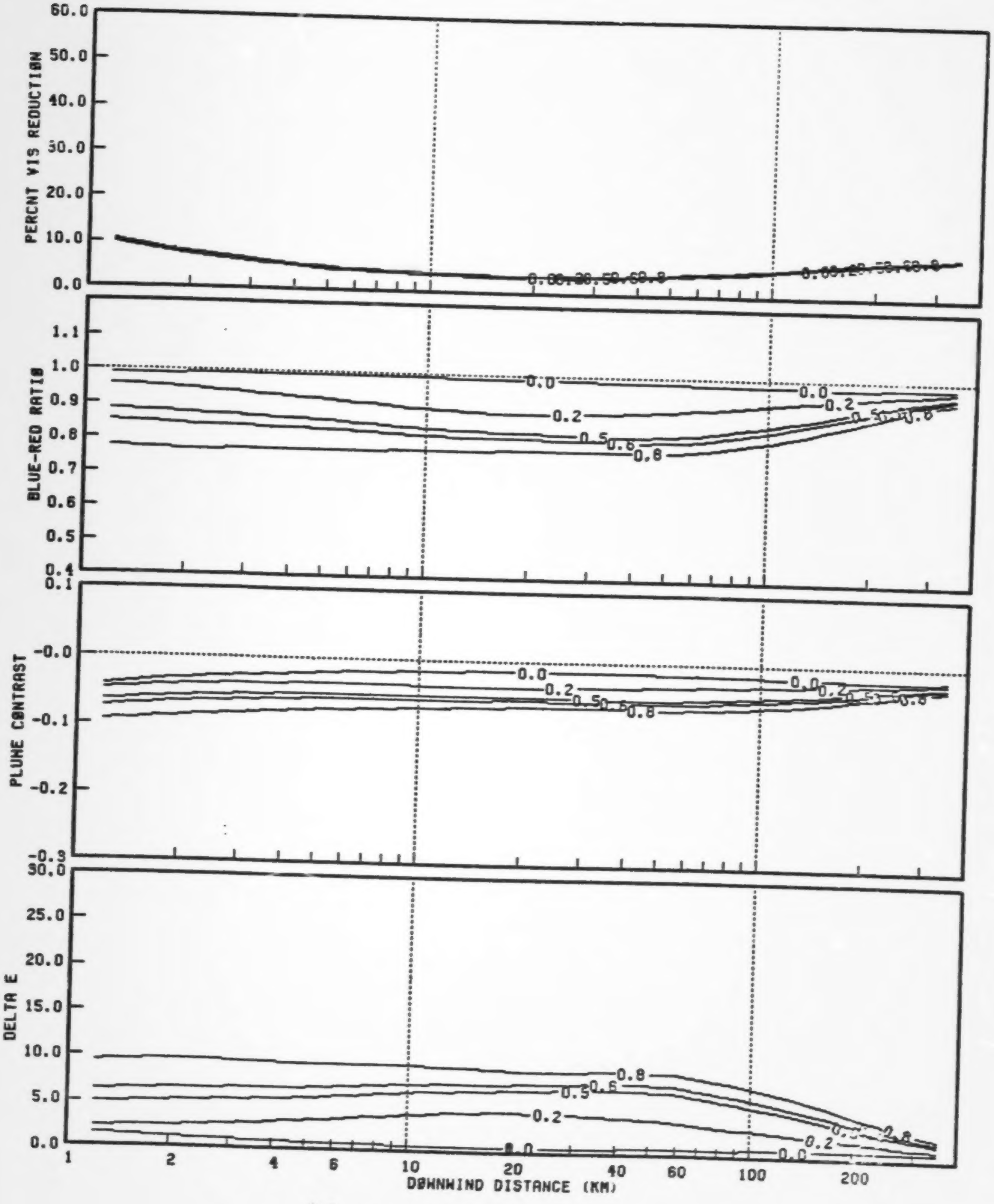
### 4. Effect of $NO_x$ Emission Rates on Visibility Impairment

Figures 9(a) through 9(d) show the effect of various $NO_x$ emission rates of 0, 0.2, 0.5, 0.6, and 0.8 lb/$10^6$ Btu on visibility impairment assuming a fixed $SO_2$ emission rate of 0.5 lb/$10^6$ Btu. These figures show the effects for a 2000 Mwe power plant; impairment calculations for 500, 1000, and 3000 Mwe power plants are shown in the figures in the appendices.



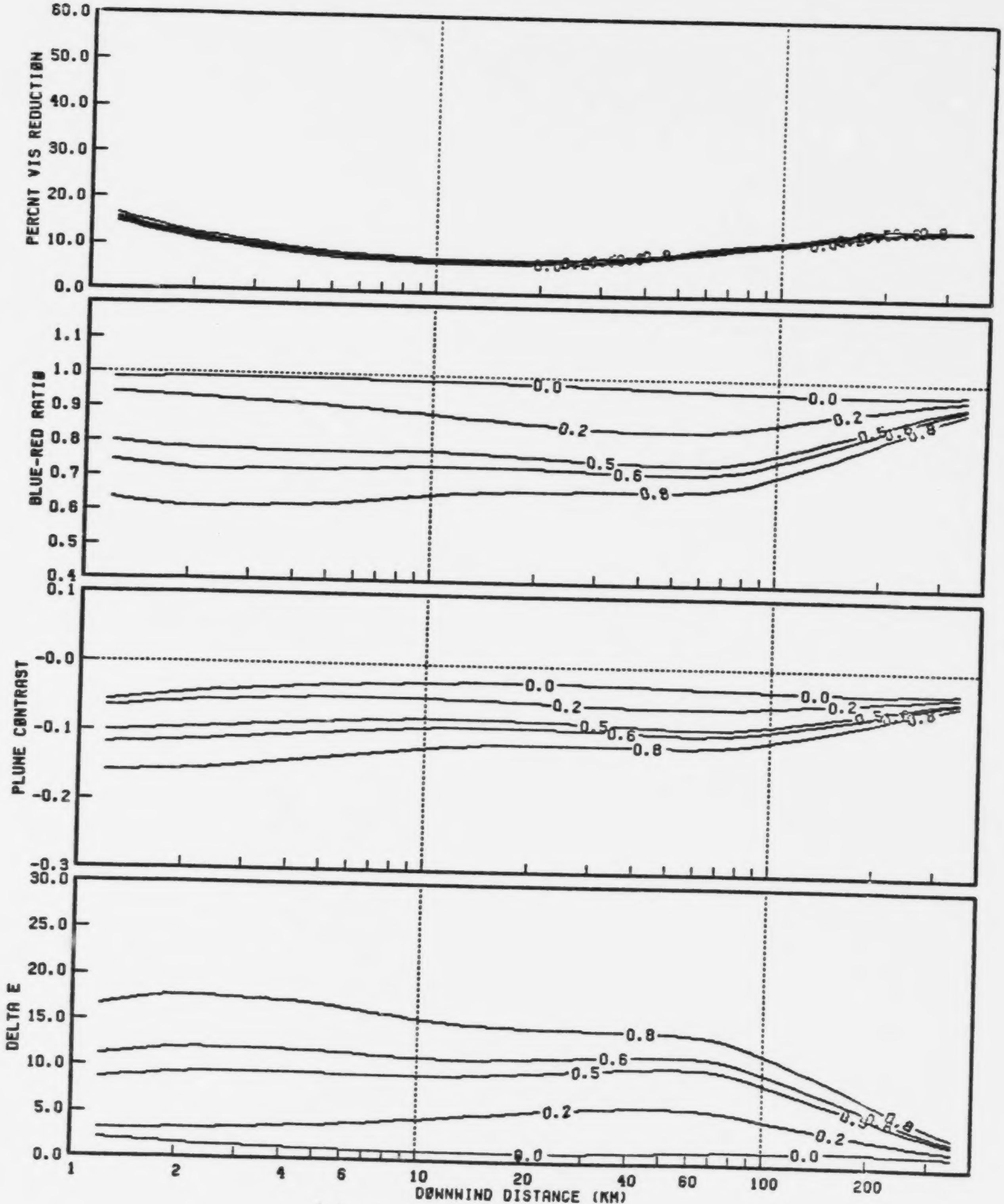
(a) Pasquill Stability C

FIGURE 9. EFFECT OF $NO_x$ EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 2000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. $NO_x$ emissions rates in pounds per million Btu are indicated.



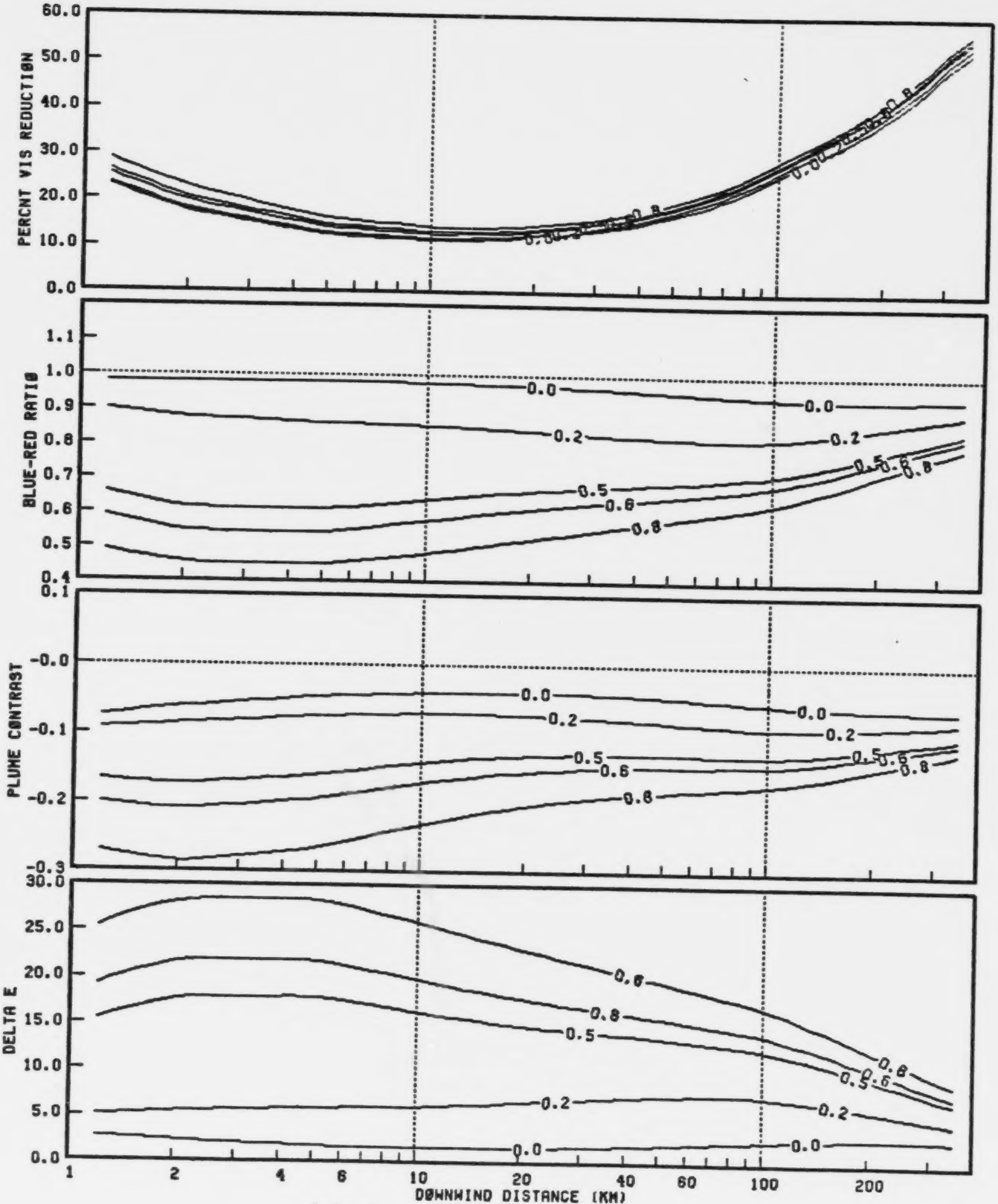
(b) Pasquill Stability D

FIGURE 9 (Continued)



(c) Pasquill Stability E

FIGURE 9 (Continued)



(d) Pasquill Stability F

FIGURE 9 (Concluded)

Varying the $NO_x$ emission rate has a negligible effect on visual range because it is assumed that nitrate aerosol is not formed. (This assumption should be checked in future plume measurement programs.) However, the $NO_x$ emission rate has a strong effect on plume discoloration. On the basis of Figures 9(c) and 9(d), plume discoloration could be virtually eliminated with efficient $NO_x$ control by reducing $NO_x$ emission rates to less than 0.2 $lb/10^6$ Btu.

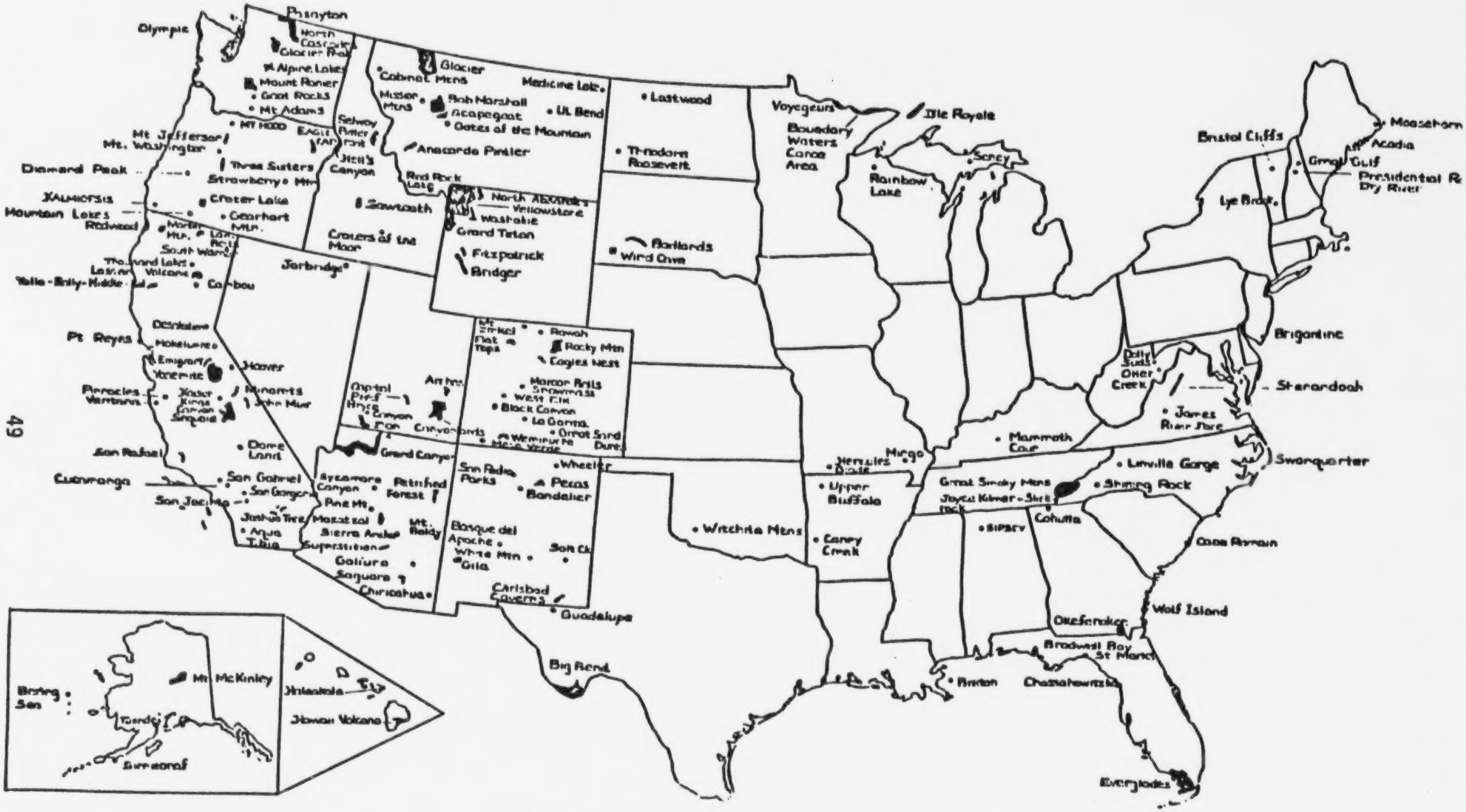
## D. AIR QUALITY CONSTRAINTS ON POWER PLANT SITING

We have identified three significant constraints on power plant siting related to air quality:

- Exceedances of PSD increments in elevated terrain areas due to excessive 3-hour- and 24-hour-average $SO_2$ concentrations resulting from plume impingement.
- Exceedances of PSD increments in Class I areas due to excessive 3-hour- and 24-hour-average $SO_2$ concentrations during limited-mixing conditions.
- Impairment of visibility in Class I areas caused by increases in haziness due to $SO_x$ emissions and the appearance of dark yellow or brown haze from $NO_x$ emissions.

The first constraint potentially limits siting alternatives in complex terrain; the others may limit siting near Class I areas.

Figure 10 shows the locations of mandatory Class I areas in the United States; many additional areas may be redesignated Class I in the near future. Using the methods and results presented in this report, it is suggested that, regardless of which of the alternate $SO_2$ emission floors for the New Source Performance Standards are selected, large coal-fired power plants may in many cases have to be sited about 100 km from Class I areas.



Olympic
Pasnyton
North Cascades
Glacier Peak
Alpine Lakes
Mount Ranier
Goat Rocks
Mt Adams
MT HOOD
Eagle Cap
Mt Jefferson
Mt. Washington
Diamond Peak
Three Sisters
Strawberry Mtn
Kalmiopsis
Crater Lake
Mountain Lakes
Gearhart Mtn.
Redwood
Marble Mtn.
Lava Beds
South Warner
Thousand Lakes
Lassen Volcanic
Yolla-Bolly-Middle Eel
Caribou
Desolation
Pt Reyes
Mokelumne
Emigrant
Yosemite
Hoover
Pinnacles
Ventana
Kaiser
Kings Canyon
Sequoia
Minarets
John Muir
Dome Land
San Rafael
Cucamonga
San Gabriel
San Gorgonio
San Jacinto
Joshua Tree
Agua Tibia
Selway Bitter Root
Hell's Canyon
Sawtooth
Craters of the Moon
Jarbidge
Glacier
Cabinet Mtns
Mission Mtns
Bob Marshall
Scapegoat
Gates of the Mountain
Anaconda Pintler
Medicine Lake
UL Bend
Red Rock Lake
North Absaroka
Yellowstone
Washakie
Grand Teton
Fitzpatrick
Bridger
Lostwood
Theodore Roosevelt
Badlands
Wind Cave
Capitol Reef
Bryce Canyon
Zion
Arches
Canyonlands
Grand Canyon
Sycamore Canyon
Petrified Forest
Pine Mt.
Mazatzal
Sierra Ancha
Mt. Baldy
Superstition
Galiuro
Saguaro
Chiricahua
Mt Zirkel
Flat Tops
Rawah
Rocky Mtn
Eagles Nest
Maroon Bells Snowmass
West Elk
Black Canyon
La Garita
Great Sand Dunes
Weminuche
Mesa Verde
San Pedro Parks
Wheeler
Pecos
Bandelier
Bosque del Apache
White Mtn
Gila
Salt Cr
Carlsbad Caverns
Guadalupe
Big Bend
Wichita Mtns
Voyageurs
Boundary Waters Canoe Area
Isle Royale
Rainbow Lake
Seney
Hercules Glade
Mingo
Upper Buffalo
Caney Creek
Mammoth Cave
Great Smoky Mtns
Joyce Kilmer-Slick rock
Sipsey
Cohutta
Linville Gorge
Shining Rock
Dolly Sods
Otter Creek
James River Face
Shenandoah
Swanquarter
Cape Romain
Wolf Island
Okefenokee
Bradwell Bay
St Marks
Breton
Chassahowitzka
Everglades
Brigantine
Lye Brook
Bristol Cliffs
Great Gulf
Presidential R. Dry River
Moosehorn
Acadia
Bering Sea
Mt McKinley
Tuxedni
Simeonof
Haleakala
Hawaii Volcano

FIGURE 10. MANDATORY CLASS I AREAS

# IV CUMULATIVE IMPACTS OF POWER PLANTS WITHIN A REGION

Another consideration in evaluating the implications of alternative New Source Performance Standards for power plants is the maximum number of power plants that can be sited in a given region without causing exceedances of PSD increments.

## A. A GENERIC REGIONAL MODEL

As a first step in estimating these maximum siting capacities, we developed a simple regional air quality model that can be used to calculate the cumulative impacts of many power plants. The basic assumption used in formulating this model is that the distribution of new power plant sites throughout a region is such that emissions are uniformly mixed between the ground and an elevated stable layer at some downwind distance. Under this assumption of distributed emissions sources and uniformly mixed emissions, we do not have to account for rates of vertical and horizontal atmospheric dispersion.

Figure 11 illustrates the conceptual basis for the regional siting capacity calculations. The objective of the calculations is to determine the concentrations of emissions from several power plants sited throughout a region having dimensions $X_R$ and $Y_R$ at a receptor location such as the shaded vertical plane shown in Figure 12. In these calculations, it is assumed that concentrations are uniformly mixed between the ground and the top of the mixed layer, which has a height $H_m$. Emissions are transported in this mixed layer by a wind of velocity u. The regional $SO_2$ concentrations may be increased as a function of the downwind distance x as a result of emissions from additional sources, or they may be decreased as a result of surface deposition, precipitation scavenging, and conversion to sulfate.

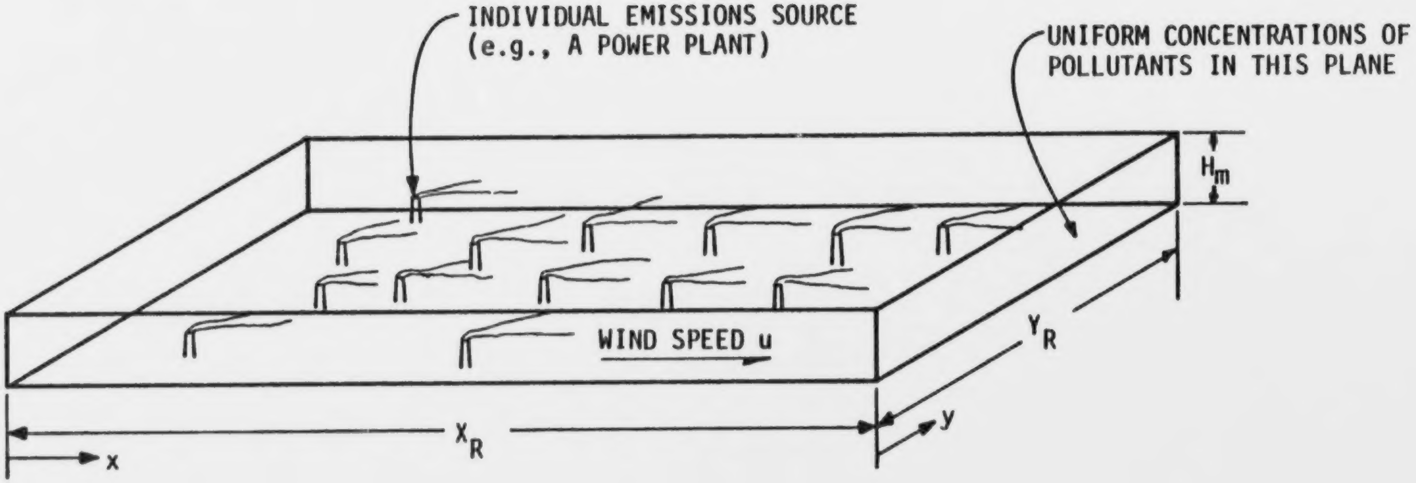

INDIVIDUAL EMISSIONS SOURCE
(e.g., A POWER PLANT)
UNIFORM CONCENTRATIONS OF
POLLUTANTS IN THIS PLANE
$H_m$
WIND SPEED u
$Y_R$
$X_R$
x
y

FIGURE 11. CONCEPTUAL BASIS FOR REGIONAL SITING CAPACITY CALCULATIONS

We can calculate the concentration at any given downwind distance x (or transit time t) using a simple box model formula:

$$\chi = \frac{Q(t)}{uH_m} \quad . \tag{11}$$

The pollutant flux Q per unit crosswind distance y may be increased if the air parcel is transported over emissions sources $Q_o$ or may be decreased as a result of surface deposition, precipitation scavenging, and chemical conversion to sulfate. For convenience, we treat the contributions of individual sources $Q_o$ as distributed sources of emission density q:

$$q = \frac{Q_o}{x_s^2} \quad , \tag{12}$$

where

$q$ = emission density ($g/m^2/sec$),
$Q_o$ = individual source emission rate (g/sec),
$x_s$ = average source spacing (m).

Ignoring periods of precipitation, we can write a mass balance for regional $SO_2$ mass flux as follows:

$$dQ = qu\ dt - \left(\frac{Q}{uH_m}\right) v_d u\ dt - kQ\ dt \quad , \tag{13}$$

where $v_d$ = deposition velocity of $SO_2$ (m/sec) and k = $SO_2$ to $SO_4^=$ rate constant (per sec). Thus, the resulting equation is:

$$\frac{dQ}{dt} + \left(k + \frac{v_d}{H_m}\right) Q = qu \quad . \tag{14}$$

The solution to Eq. (14) as a function of air parcel travel time is:

$$Q(t) = \frac{qu}{k'}\left(1 - e^{-k't}\right) \quad , \tag{15}$$

where $k' = k + (v_d/H_m)$.

By combining Eqs. (11) and (15), we obtain:

$$\chi = \frac{q\left(1 - e^{-k't}\right)}{k'H_m} = \frac{q\left(1 - e^{-k'x/u}\right)}{k'H_m} \quad . \tag{16}$$

Thus, the $SO_2$ concentration $\chi$ downwind of a region of emission density q is directly proportional to q and indirectly proportional to the mixing depth $H_m$. If the air parcel travel time is large over the region of emission density q, the resultant $SO_2$ concentration is simply:

$$\chi = \frac{q}{k'H_m} \quad . \tag{17}$$

Equation (16) is appropriate for estimating concentrations immediately downwind of an area with emission density q. However, as previously shown, new power plants cannot be sited within some particular distance of a Class I area because of the need to ensure that individual sources do not violate Class I PSD increments. Consequently, over a distance on the order of 100 km, an air parcel will be transported over areas with zero incremental emission densities $\Delta q$ (above levels existing when PSD legislation was enacted). Thus, $SO_2$ flux is decreased somewhat by conversion to sulfate and by surface deposition within these exclusion areas around Class I areas. Equation (16) can be modified as follows to account for this effect of exclusion areas around Class I areas:

$$\chi = \frac{q\left(1 - e^{-k'T_R}\right)e^{-k'T_0}}{k'H_m} \quad , \tag{18}$$

where $T_0$ is the air parcel transit time over the area surrounding the Class I region where power plants cannot be sited and $T_R$ is the transit time over the region in which emissions sources are located.

Similar equations can be derived for sulfate fluxes Q' and concentrations $\chi'$ if we ignore surface deposition of sulfate (an appropriate assumption since a negligible amount of sulfate is deposited during periods without precipitation) and precipitation scavenging (an appropriate assumption only for periods without precipitation). Thus, we have:

$$\frac{dQ'}{dt} = 1.5\ kQ \tag{19}$$

$$\chi' = \frac{1.5\ kq}{k'H_m}\left[T_R - \frac{1}{k'}\left(1 - e^{-k'T_R}\right)e^{-k'T_0}\right] \quad . \tag{20}$$

Note from Eq. (20) that, unlike $SO_2$ concentrations, sulfate concentrations continue to increase with transit time over a region unless precipitation occurs and scavenges the aerosol [see, for example, the plot of sulfate flux in Figure 6(a)].

We can use Eq. (18) to estimate the maximum increment in emission density $\Delta q$ allowed by PSD increments $\Delta\chi_{PSD}$. The value of $\Delta q$ can be used to calculate the siting capacity in megawatts of coal-fired power plants in a region of known area.

## B. MAXIMUM REGIONAL $SO_2$ EMISSION DENSITIES AND POWER PLANT SITING CAPACITIES

It can be shown that the Class I 24-hour-average $SO_2$ increment of 5 $\mu g/m^3$ is the most limiting PSD increment for the regional siting capacity. A limited-mixing situation with a stable capping layer persisting over a period of three to five days without precipitation appears to be the meteorological condition most likely to cause exceedances of the 24-hour $SO_2$ PSD increment in Class I areas due to regional emissions. According to an analysis by Holzworth (1972), this condition occurs more than once per year in most areas of the United States. In the East, this condition is associated with mixing depths up to 2000 m, whereas in the West the associated mixing depths are less than 1000 m.

With these mixing depths, we calculated the maximum regional emission densities necessary to meet Class I PSD increments using Eq. (18) modified as follows:

$$\Delta q = \frac{\Delta \chi_{PSD}\, k' H_m}{\left(1 - e^{-k' T_R}\right) e^{-k' T_0}} \quad . \qquad (21)$$

Maximum emission densities of 0.081 $g/km^2/sec$ for the western United States ($H_m$ = 1000 m) and 0.107 $g/km^2/sec$ for the eastern United States ($H_m$ = 2000 m) were computed using Eq. (21) and the following values of parameters:

$\Delta \chi_{PSD}$ = 5 $\mu g/m^3$ (Class I 24-hour-average $SO_2$ increment),

$k' = k + (v_d/H_m)$,

k = 0.005 per hour ($SO_2$-to-sulfate conversion pseudo-first-order rate constant),

$v_d$ = 1 cm/sec ($SO_2$ deposition velocity),

$T_R$ = 2 days (air parcel travel time over the emissions areas),

$T_0$ = 5 hours (air parcel travel time over the exclusion area between the emissions area and the Class I area).

We can translate these maximum $SO_2$ emission densities into maximum power plant regional siting capacities in terms of megawatts of coal-fired generating capacity per square kilometer if we know the $SO_2$ emission rates. ICF Incorporated (1978) has calculated average regional $SO_2$ emission rates corresponding to each of the alternative NSPS $SO_2$ emission floors of 0.2, 0.5, and 0.8 $lb/10^6$ Btu, as well as the current NSPS limit of 1.2 $lb/10^6$ Btu, for the eastern and western United States. These emission rates are shown in Table 2, which also presents the maximum power plant regional siting capacities for each of these cases.

Using the results shown in Table 2, we estimated the maximum power plant siting capacity in the contiguous United States from the standpoint of air quality (PSD) considerations. From estimates of power plant siting constraints imposed by Class I areas, we estimated that approximately 40 percent of the land area of the western United States (the states of and westward of Montana, Wyoming, Colorado, and New Mexico) could be used for power plant siting. That area totals 1.3 million km$^2$. In the eastern United States, more than 90 percent of the land area would be left unrestricted for power plant siting from the standpoint of Class I area protection. That area totals 2.8 million km$^2$. By multiplying the siting capacities shown in Table 2 by these areas, we determined the maximum additional coal-fired power plant capacity that can be installed in the United States, assuming different NSPS limitations. The results of this calculation are displayed in Table 3.

TABLE 2. REGIONAL AVERAGE $SO_2$ EMISSION RATES AND MAXIMUM POWER PLANT SITING CAPACITIES

| NSPS $SO_2$ Emission Floor (lb/10$^6$ Btu) | Eastern United States | | Western United States | |
|---|---|---|---|---|
| | $SO_2$ Emissions (lb/10$^6$ Btu) | Siting Capacity (Mwe/km$^2$) | $SO_2$ Emissions (lb/10$^6$ Btu) | Siting Capacity (Mwe/km$^2$) |
| 0.2 | 0.42 | 0.22 | 0.18 | 0.40 |
| 0.5 | 0.42 | 0.22 | 0.28 | 0.25 |
| 0.8 | 0.52 | 0.18 | 0.48 | 0.15 |
| 1.2 | 0.96 | 0.10 | 0.80 | 0.09 |

The maximum increment in power plant siting capacity for each of the proposed NSPS $SO_2$ floors are well above the 400 gigawatt electric (Gwe) output of coal-fired generating capacity that was predicted by ICF Incorporated (1978) to be installed during the period 1975 to 1995. However, with the current NSPS limit of 1.2 lb/10$^6$ Btu, planned capacity additions over the period 1975 to 1995 would use up 80 percent of the estimated U.S. power plant siting capacity. It appears that any of the floors studied for the proposed

NSPS $SO_2$ standard will be adequate to ensure that a sufficient number of coal-fired power plants can be built to meet growing energy needs while air quality goals are being met. Obviously, a greater number of power plants can be built in a given region and more area will be available for power plant siting with the implementation of more restrictive $SO_2$ emission controls.

TABLE 3. MAXIMUM POWER PLANT SITING CAPACITIES IN THE CONTIGUOUS UNITED STATES

(gigawatts of electric output*)

| NSPS $SO_2$ Emission ($lb/10^6$ Btu) | Eastern United States† | Western United States§ | Total |
|---|---|---|---|
| 0.2 | 836 | 520 | 1356 |
| 0.5 | 836 | 325 | 1161 |
| 0.8 | 684 | 195 | 879 |
| 1.2 | 380 | 117 | 497 |

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* 1 Gwe = 1000 Mwe.

† Maximum regional $SO_2$ emissions
= $(3.8 \times 10^6\ km^2)(0.107\ g/km^2/sec)$ = 39,000 tons per day.

§ Maximum regional $SO_2$ emission rate
= $(1.3 \times 10^6\ km^2)(0.081\ g/km^2/sec)$ = 10,000 tons per day.

## C. IMPACT OF MAXIMUM $SO_2$ EMISSION DENSITY ON REGIONAL VISUAL RANGE

We evaluated the impact of the maximum regional $SO_2$ emission density calculated in the previous section on regional sulfate concentrations and the resulting impacts on visibility (visual range) as described below.

Using Eq. (20), we calculated the maximum increase in 24-hour-average sulfate concentration resulting from the calculated maximum allowable incremental increases in regional $SO_2$ emission density of 0.081 and 0.107 g/km$^2$/sec for the western and eastern United States, respectively. These maximum sulfate increments were calculated to be approximately 1.7 $\mu g/m^3$ for the western United States and 1.4 $\mu g/m^3$ for the eastern United States.

Using appropriate values of scattering efficiency ($b_{scat}$-to-mass ratios) for the eastern and western United States [0.08 and 0.04 x $10^{-4}$/m/($\mu g/m^3$), respectively], we calculated the incremental increases in scattering coefficient corresponding to these increases in sulfate concentration and the resultant reductions in visual range. Assuming an average background visual range of 130 and 15 km, respectively, for the western and eastern United States, these increases in sulfate concentration would cause the following reductions in visual range in Class I areas during worst-case limited-mixing conditions:

- 18 percent in the western United States.
- 4 percent in the eastern United States.

During more typical, well-ventilated conditions, visual range would be reduced about 4 percent in the western United States and 1 percent in the eastern United States. Thus, it appears that limits to growth in regional $SO_2$ emission density imposed by effective enforcement of Class I area PSD increments will be effective in limiting the reductions in visual range in Class I areas.

# V SUMMARY AND CONCLUSIONS

We have analyzed the impact of various sizes of power plants, which emit $SO_2$ and $NO_x$ at various rates, using analysis methods either recommended by or likely to be accepted by the EPA to estimate air quality impacts and visibility impairment caused by single power plant plumes and by cumulative emissions on a regional scale. On the basis of these analyses, we have drawn tentative conclusions* that are significant to air quality planning in the following areas:

- > Air quality impacts caused by individual power plants.
- > Visibility impairment.
- > Constraints on power plant siting.
- > Cumulative regional impacts.
- > Implications for emission control.
- > Needs for further research.

## A. AIR QUALITY IMPACTS CAUSED BY INDIVIDUAL POWER PLANTS

Our tentative conclusions about the air quality impacts of individual power plants are as follows:

- > The Prevention of Significant Deterioration Regulations, which limit increases in 3-hour- and 24-hour-average $SO_2$ concentrations, impose the most restrictive limitations on power plant emissions and siting.
- > Maximum 3-hour- and 24-hour-average $SO_2$ Class I area increments will restrict the siting of and $SO_2$ emissions from coal-fired power plants located in Class II areas as far as 100 to 200 km away from Class I areas.

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* Because these conclusions are generic in nature, they should not be applied to a given power plant application without consideration of the site-specific emissions conditions, meteorology, and topography.

> Limited mixing conditions, during which vertical mixing of emissions is restricted by stable layers 500 to 1000 m above the ground, are likely to be associated with the highest 3-hour- and 24-hour-average $SO_2$ ground-level concentrations; however, in complex terrain areas even higher ground-level concentrations may occur as a result of plume impingement on elevated terrain.

> Surface deposition of $SO_2$ and conversion of $SO_2$ to sulfate must be considered in models that are designed to calculate impacts beyond 100 km from a power plant. More than half of the initially emitted $SO_2$ will be lost by surface deposition at distances greater than 200 km during light-wind, limited mixing conditions.

> The wind speed that maximizes the impact of power plant emissions on ground-level $SO_2$ concentrations increases linearly with the downwind distance of the receptor of concern. Thus, maximum concentrations at 100 km downwind are likely to occur with light winds (1 to 2 m/sec), whereas those at 200 to 500 km are likely to occur with moderate winds (3 to 6 m/sec).

> Maximum ground-level surface concentrations are not likely to occur less than 100 km downwind; however, plume centerline concentrations of sulfate are likely to remain relatively constant with downwind distance since plume dilution is counterbalanced by additional sulfate formation.

> Sulfate mass fluxes tend to increase monotonically with downwind distance, whereas $NO_2$ fluxes appear to reach maxima between 20 and 100 km downwind of the power plant, depending on atmospheric stability.

> The fraction of initial $SO_x$ or $NO_x$ emissions that has been deposited by the time a plume parcel is transported to a given downwind distance depends on the travel time, the rate of plume mixing, ground-level concentrations, and the deposition velocity.

## B. VISIBILITY IMPAIRMENT

With regard to visibility impairment caused by power plant emissions, we have concluded tentatively that:

> Reductions in visual range caused by power plant emissions depend on the $SO_2$ emission rate and the rate at which gaseous emissions are converted to aerosol. Assuming a 0.5 percent per hour $SO_2$-to-$SO_4^=$ conversion rate and a typical western U.S. background visual range of 130 km, a 2000 Mwe (megawatts of electric output) power plant, during worst-case dispersion conditions, will cause maximum visual range reductions of 11, 28, 40, and 51 percent as a result of $SO_2$ emission rates of 0.2, 0.5, 0.8, and 1.2 lb/$10^6$ Btu, respectively. The same plant would cause visual range reductions of 2, 4, 7, and 11 percent, respectively, if it were located in an area with a background visual range of 15 km (a value typical of the eastern United States). These estimates correspond to maximum ground-level sulfate concentrations of 1, 3, 5, and 8 $\mu g/m^3$ for $SO_2$ emission rates of 0.2, 0.5, 0.8, and 1.2 lb/$10^6$, respectively.

> These estimates of maximum visual range reduction are based on the assumptions of worst-case meteorological conditions, location of the observer at ground level within the plume 350 km from the power plant, and an observer's line of sight along the plume axis. If the observer's line of sight is perpendicular to the plume axis, visual range reductions are smaller: 4, 9, 14, and 21 percent, respectively, for the case assuming a background visual range of 130 km.

> Visual range reduction during worst-case meteorological conditions is at least a factor of 5 larger than what it would be during average meteorological conditions (with higher wind speeds and mixing depths).

> Yellow-brown plumes are expected to be visible only when the background visual range is great--for example, in the nonurban areas of the western United States--and only during stable, light-wind conditions. Since such wind conditions are expected to persist for no more than 11 to 17 hours at a time, yellow-brown plumes could be transported up to 100 to 150 km downwind from a coal-fired power plant located in the western United States.

> During typical well-mixed and ventilated atmospheric conditions, plumes from power plants meeting the proposed New Source Performance Standards would not be visible, regardless of the $SO_2$ emission rate floor.

## C. AIR QUALITY CONSTRAINTS ON POWER PLANT SITING

We have reached the following tentative conclusions about air quality constraints on power plant siting:

> Power plants that are 1000 Mwe or larger emitting 0.8 lb $SO_2/10^6$ Btu, or 2000 Mwe or larger emitting 0.5 lb $SO_2/10^6$ Btu, may cause maximum 24-hour-average ground-level $SO_2$ concentrations in excess of the PSD Class II increment of 91 $\mu g/m^3$, according to calculations based on conservative screening techniques recommended by the EPA.

> If the basic EPA Valley Model is used as a basis for evaluation, 2000 Mwe power plants will have to be sited at least 18 km away from elevated terrain if $SO_2$ emissions are well controlled (0.2 lb/$10^6$ Btu) and at least 50 km away if $SO_2$ emissions are 0.8 lb/$10^6$ Btu in order to meet Class II PSD increments. Even small (500 Mwe), well-controlled (0.2 lb $SO_2/10^6$ Btu) power plants will have to be sited at least 50 km from elevated terrain in Class I areas.

> Power plants having capacities of 2000 Mwe or larger, even with $SO_2$ emission rates as low as 0.2 lb/$10^6$ Btu, may have to be sited

about 100 km from Class I areas to meet the Class I 24-hour-average $SO_2$ PSD increment of 5 μg/$m^3$.

> In the western United States, which has excellent background visual range, large coal-fired power plants may have to be sited 100 to 150 km from Class I areas to prevent the occurrence of yellow-brown haze in scenic areas during periods of poor atmospheric dispersion.

> Since maximum reductions in visual range are estimated to occur more than 200 km downwind of a power plant, the protection of visual range in Class I areas cannot practically be achieved through constraints on siting alone.

## D. CUMULATIVE REGIONAL IMPACTS

Out tentative conclusions about the cumulative regional impacts of power plant emissions are:

> As a result of PSD Regulations, it may be necessary to limit increases in regional $SO_2$ emission density to 0.08 to 0.11 g/$km^2$/sec.

> With the above increases in regional $SO_2$ emission density, on worst-case days regional average sulfate concentrations are estimated to increase by 1 or 2 μg/$m^3$, and visual range is estimated to be reduced 18 percent in the western United States and 4 percent in the eastern United States.

> On typical days with good ventilation, reductions in visual range are estimated to be much less--about 4 percent in the western United States and 1 percent in the eastern United States.

## E. IMPLICATIONS FOR POWER PLANT EMISSION CONTROL

We have concluded tentatively that the implications of our findings for power plant emission control are the following:

> It may be necessary to limit $SO_2$ emissions from power plants to less than 1 kg/sec, or about 100 tons per day, to meet Class II PSD Standards in level terrain in the western United States. The emission rate is the equivalent of about 0.8 lb/$10^6$ Btu for a 1000 Mwe plant and 0.4 lb/$10^6$ Btu for a 2000 Mwe plant. Higher emission rates could be allowed in the eastern United States, given the less frequent occurrence of limited mixing conditions; however, even greater control may be necessary to meet those standards in complex terrain.

> If $SO_2$ emissions from power plants located in the western United States that burn low-sulfur coal are not well controlled, then siting alternatives may be restricted by the required minimum separation distance between the site and elevated terrain or Class I areas. This outcome will occur regardless of the $SO_2$ emission floor that is selected for New Source Performance Standards.

> With less stringent $SO_2$ control (increased $SO_2$ emissions), limitations become more severe on power plant size, power plant siting relative to elevated terrain and Class I areas, and the number of power plants that can be built in a region.

> It appears that with any of the anticipated $SO_2$ emission floors considered (0.2, 0.5, and 0.8 lb/$10^6$ Btu), PSD increments will not be used up within regions in the eastern United States as a result of planned power plant development in the next 20 years, assuming judicious and well-planned siting. However, as noted above, power plants located in the western United States will require full $SO_2$ control, regardless of emission standards, to meet stringent PSD Class I Regulations.

> It appears that the siting and $SO_2$ emission constraints imposed by effective enforcement of PSD Class I $SO_2$ increments may be sufficient to prevent significant visibility impairment in Class I areas during most atmospheric dispersion conditions. However, during limited mixing or stable,

light-wind conditions, visual range may be reduced by as much as 20 to 50 percent within the plume at locations more than 200 km downwind, and yellow-brown haze may be visible in Class I areas in the western United States as a result of power plant emissions as far as 100 to 150 km away. The meteorological conditions that would cause such impairment are expected to occur only a few days each year in the western United States. The incremental impact of power plant emissions on visibility in the eastern United States will be much smaller because of the relatively poor background visual range in that region.

> Control of $SO_2$ emissions from power plants will reduce impacts on visual range at locations several hundred kilometers downwind but will increase the yellow-brown plume coloration caused by $NO_x$ emissions within 100 km of the plant. Control of $NO_x$ emissions from power plants will reduce impact on visual range.

> Long term air quality and visibility goals may require both $SO_2$ and $NO_x$ emission control, particularly for large power plants located in the western United States.

## F. RESEARCH NEEDS

From the results of our study, we have determined the following needs for further research:

> Air quality simulation models that provide realistic estimates of the transport, diffusion, chemical transformation, and visual effects of power plant emissions at distances more than 50 km downwind must be developed, tested, refined, and validated.

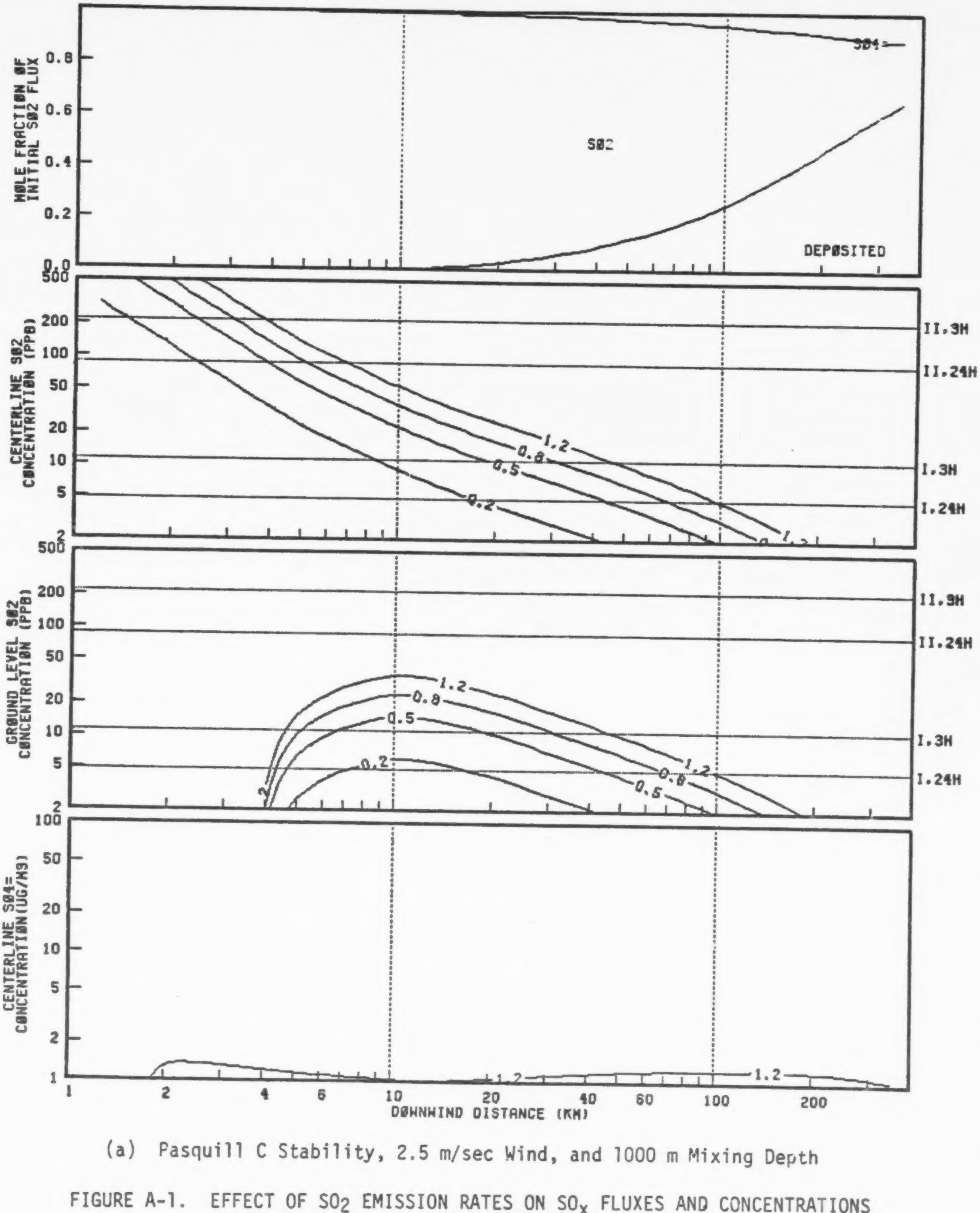
> The frequency of occurrence and persistence of meteorological conditions that cause potential exceedances of PSD increments must be quantified for different regions of the country.

> Cumulative impacts resulting from proposed new sources should be analyzed in detail. In particular, the impacts of planned regional energy development in the western United States on air quality and visibility in scenic Class I areas should be evaluated.

> Tentative conclusions based on this short study should be critically examined in future, more detailed analyses because of their significant siting and control implications.

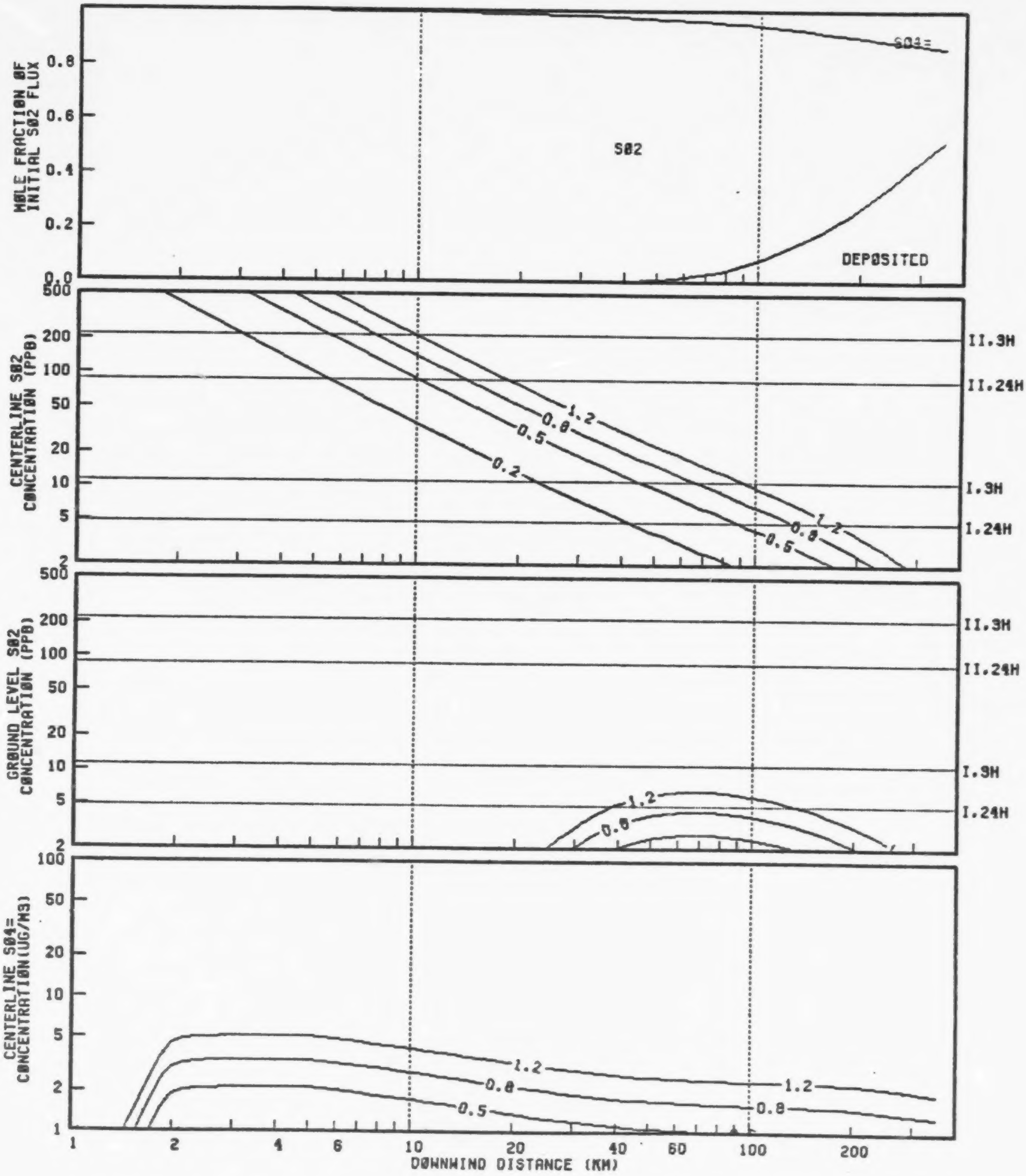
> Because of the generic nature of this study, tentative conclusions should not be applied to a given power plant evaluation without considering site-specific emission conditions, meteorology, and topography, as well as applicable regulatory requirements.

# APPENDIX A
# 500 MWE POWER PLANT IMPACTS



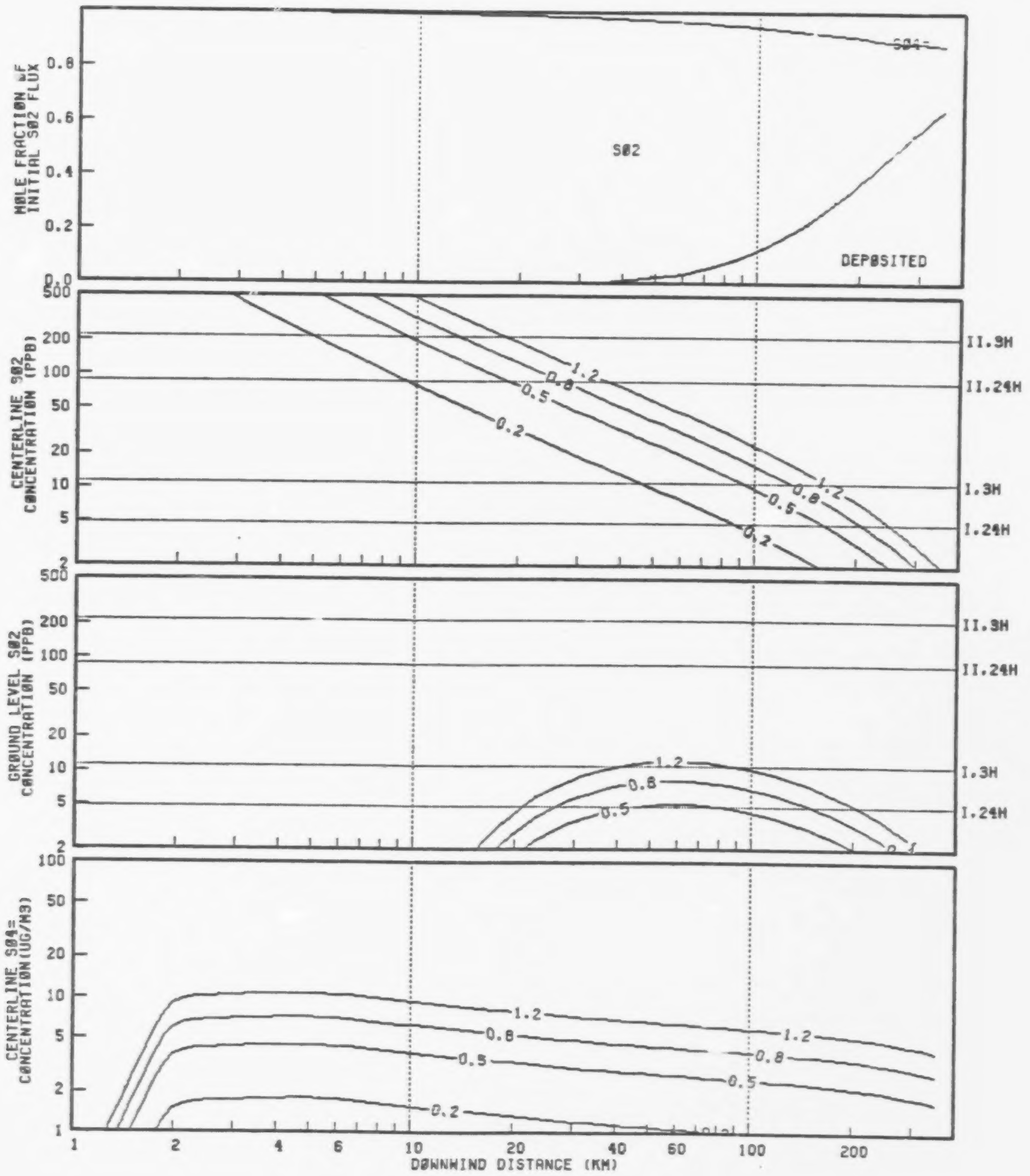
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE A-1. EFFECT OF $SO_2$ EMISSION RATES ON $SO_x$ FLUXES AND CONCENTRATIONS DOWNWIND OF A 500 Mwe COAL-FIRED POWER PLANT. $SO_2$ emission rates in pounds per million Btu are indicated.



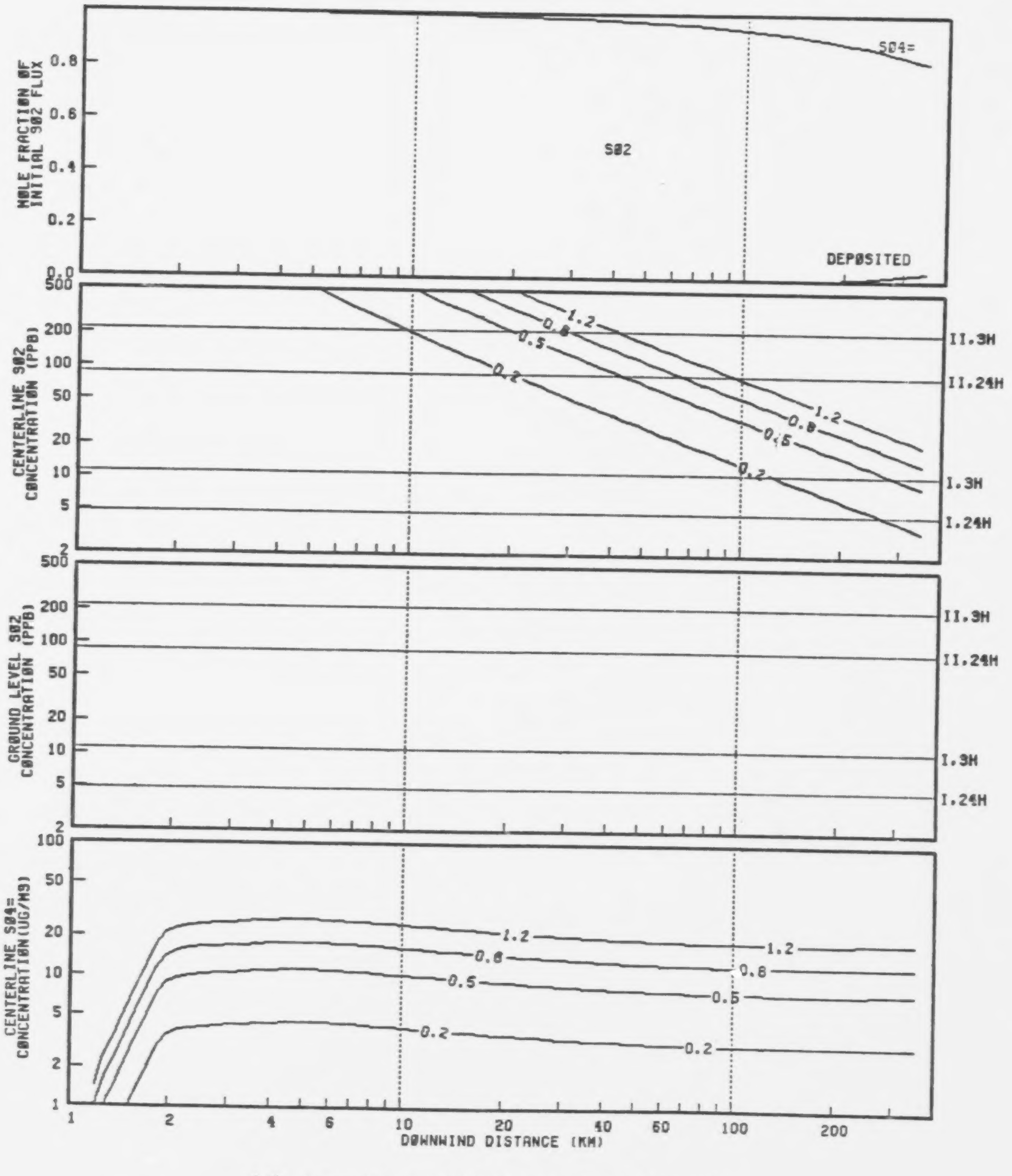
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE A-1 (Continued)



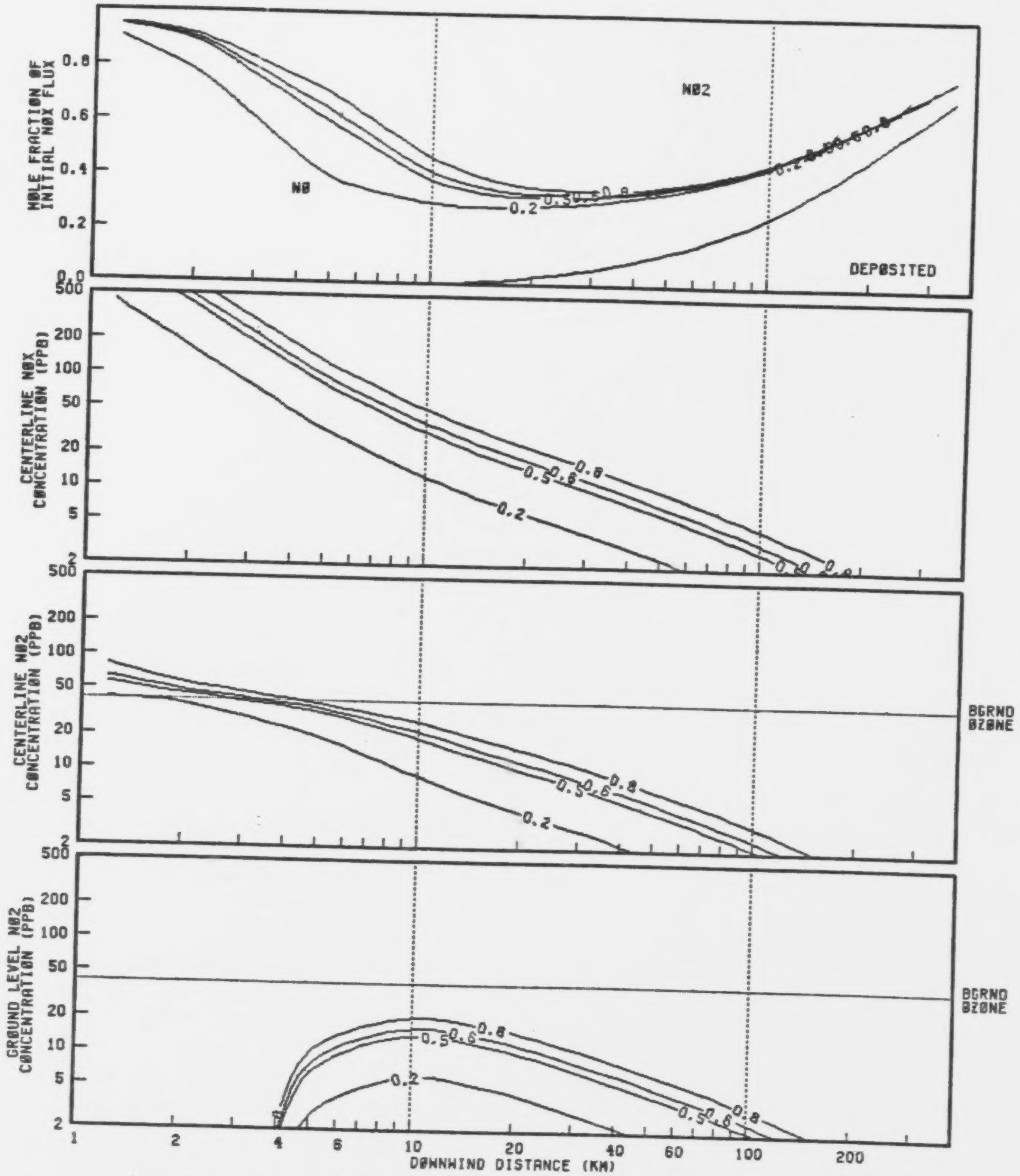
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE A-1 (Continued)



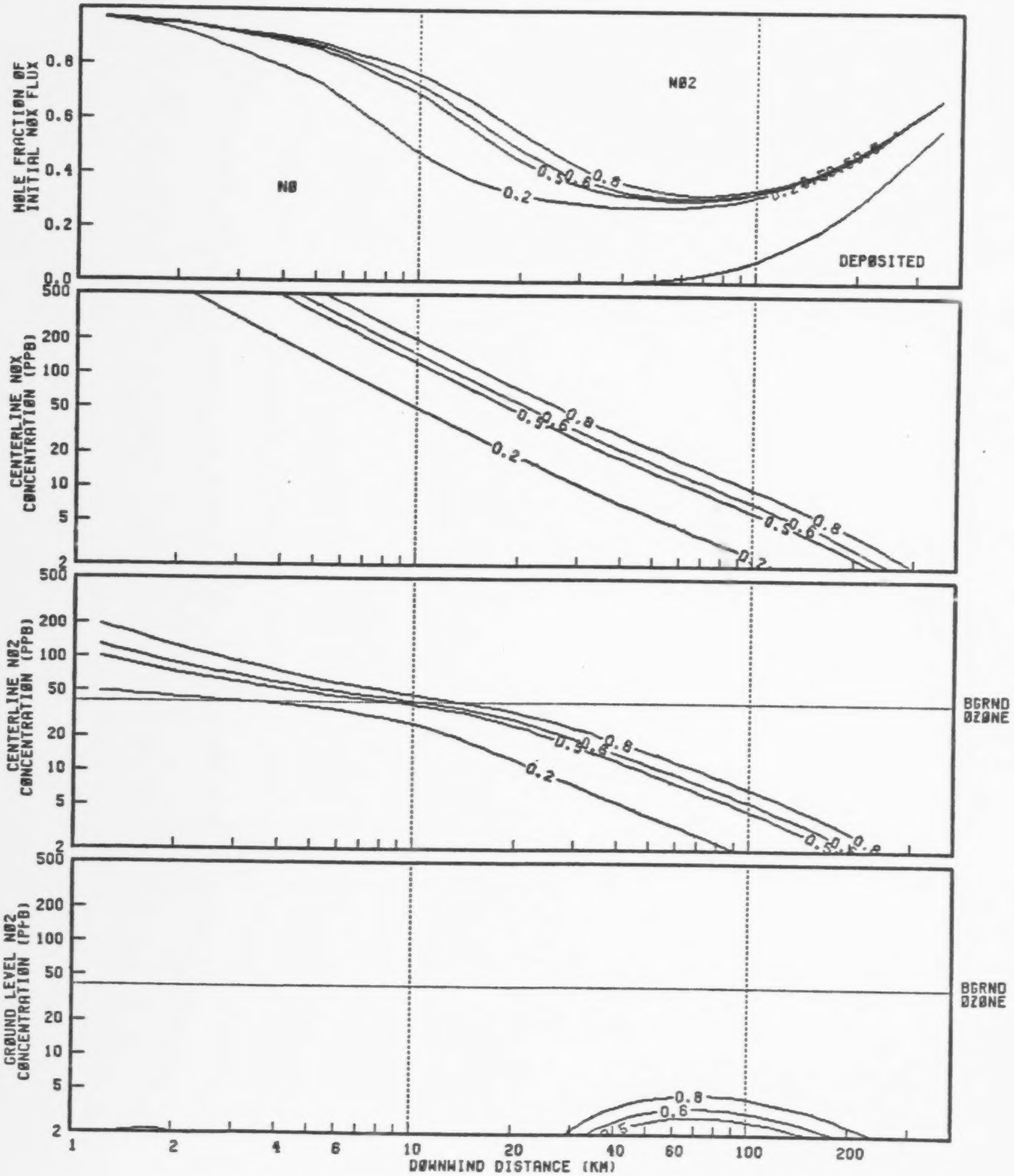
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE A-1 (Concluded)



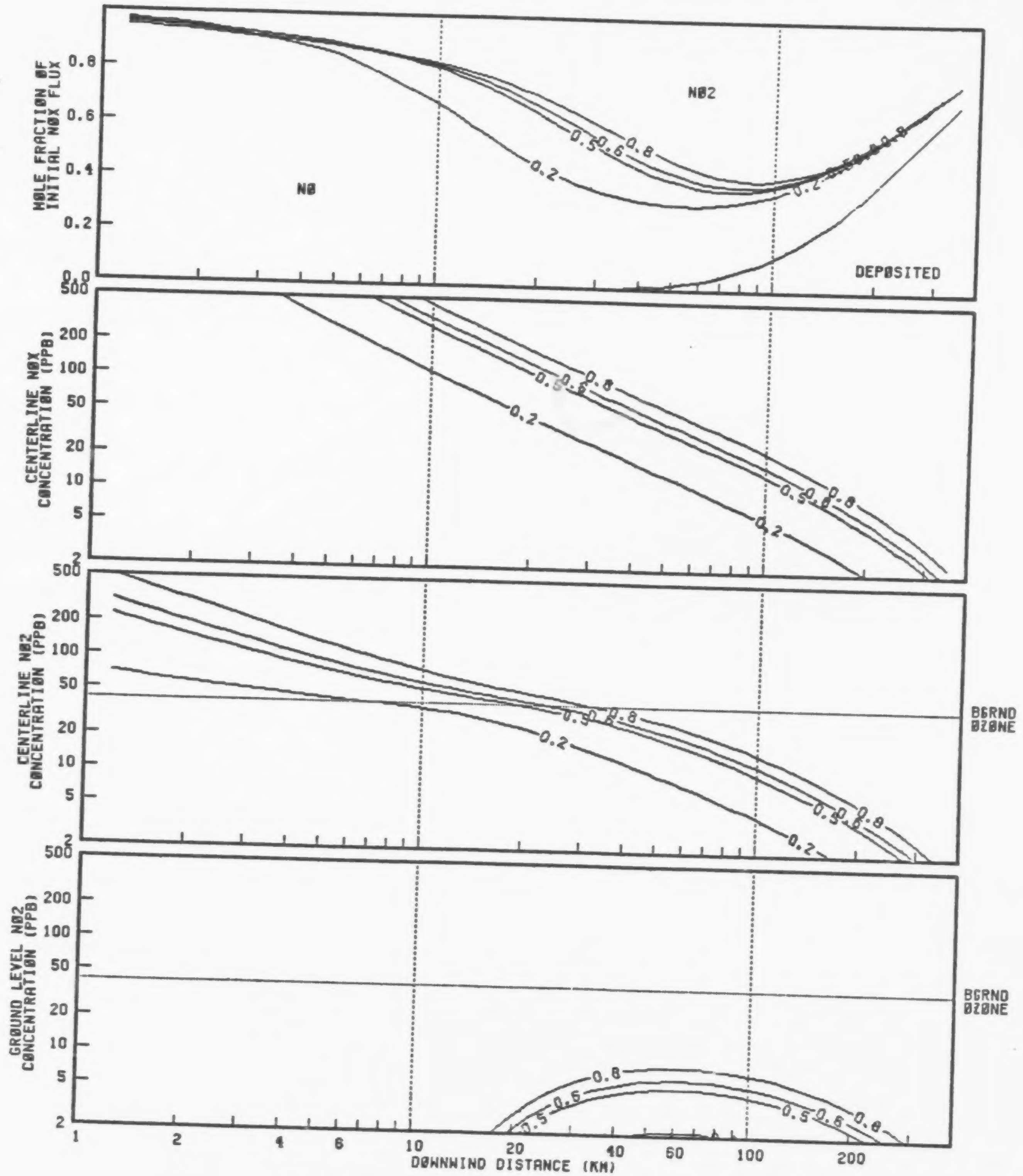
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE A-2. EFFECT OF $NO_x$ EMISSION RATES ON $NO_x$ FLUXES AND CONCENTRATIONS DOWNWIND OF A 500 Mwe COAL-FIRED POWER PLANT. $NO_x$ emission rates in pounds per million Btu are indicated.



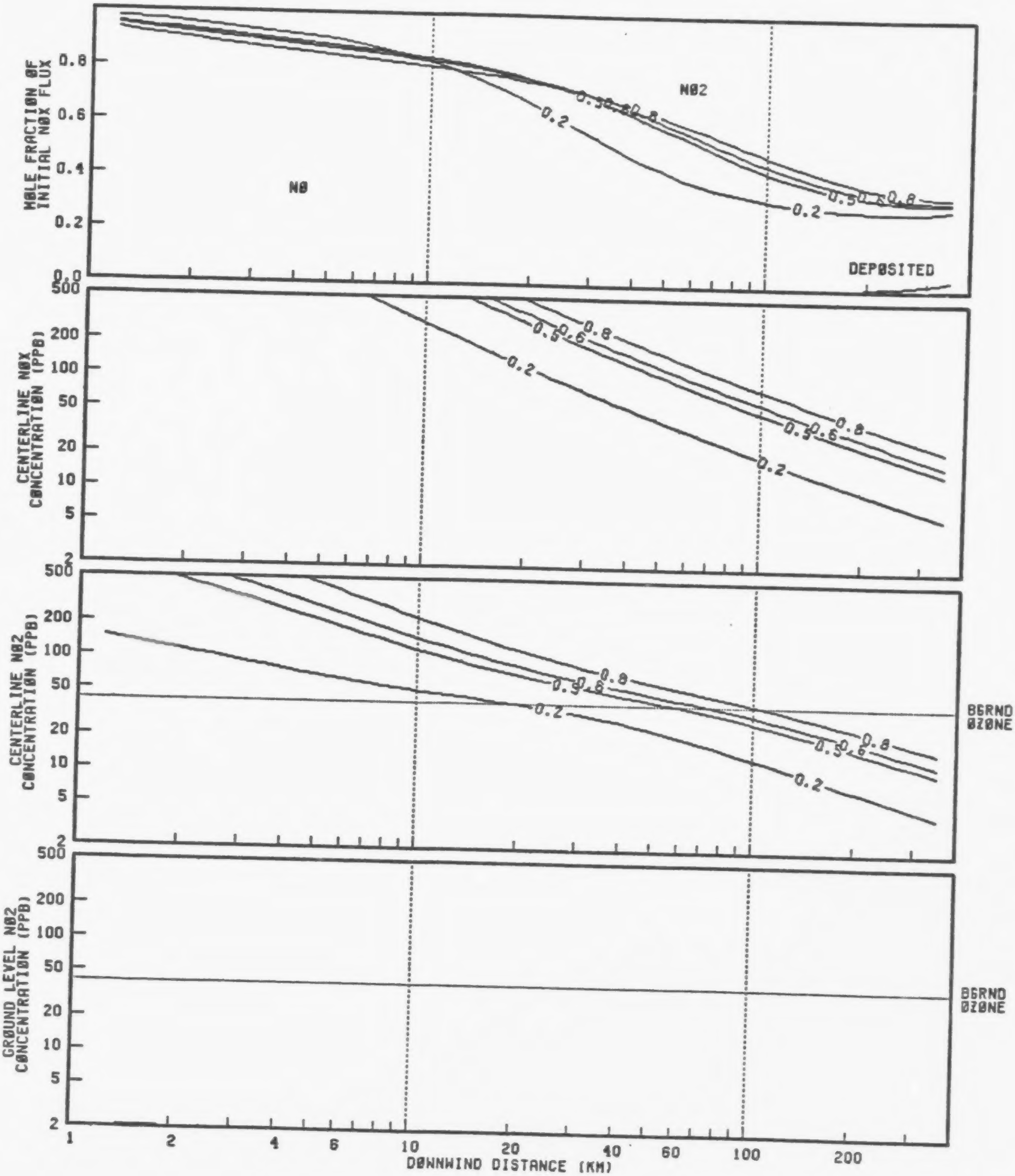
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE A-2 (Continued)



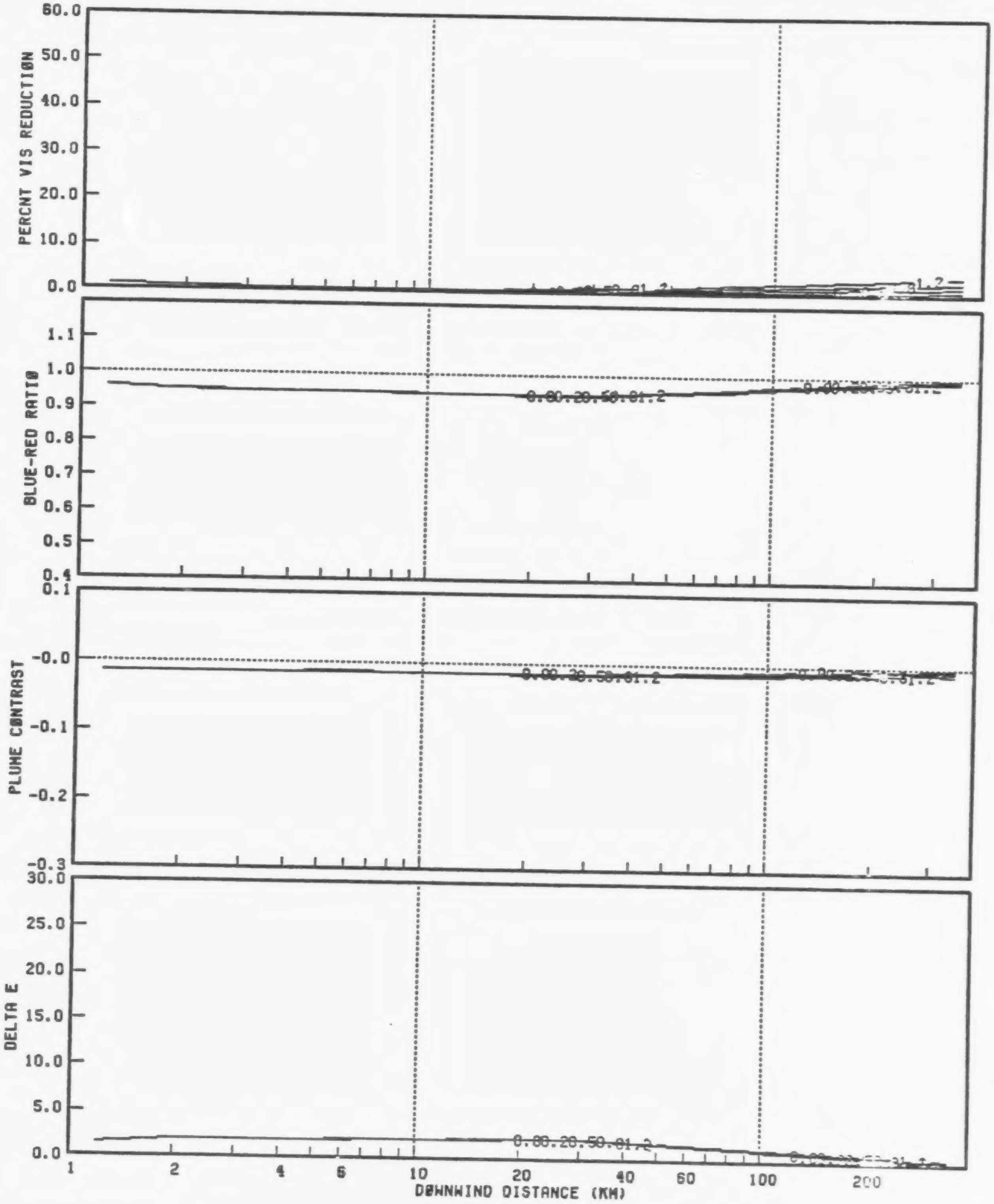
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE A-2 (Continued)



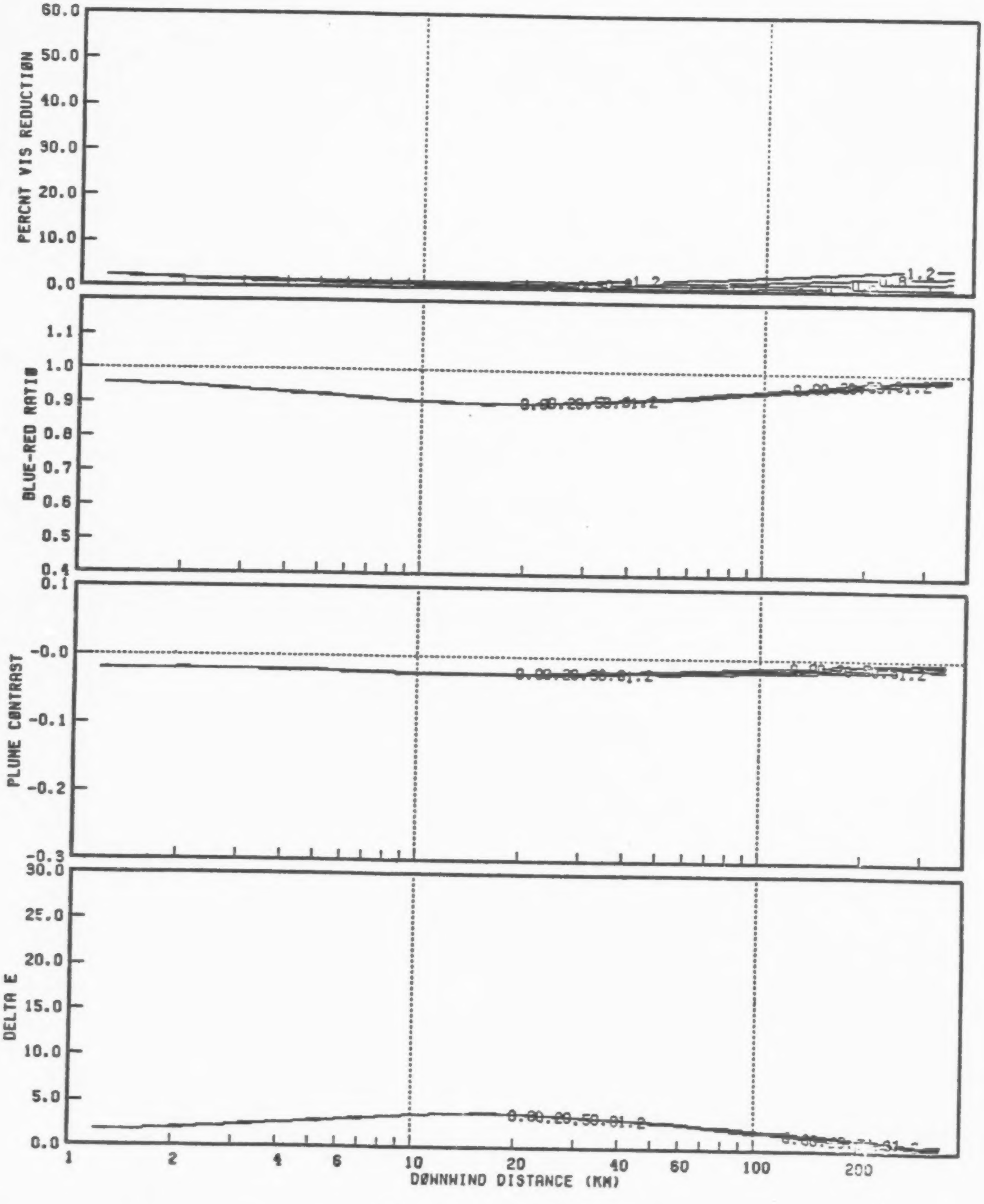
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE A-2 (Concluded)



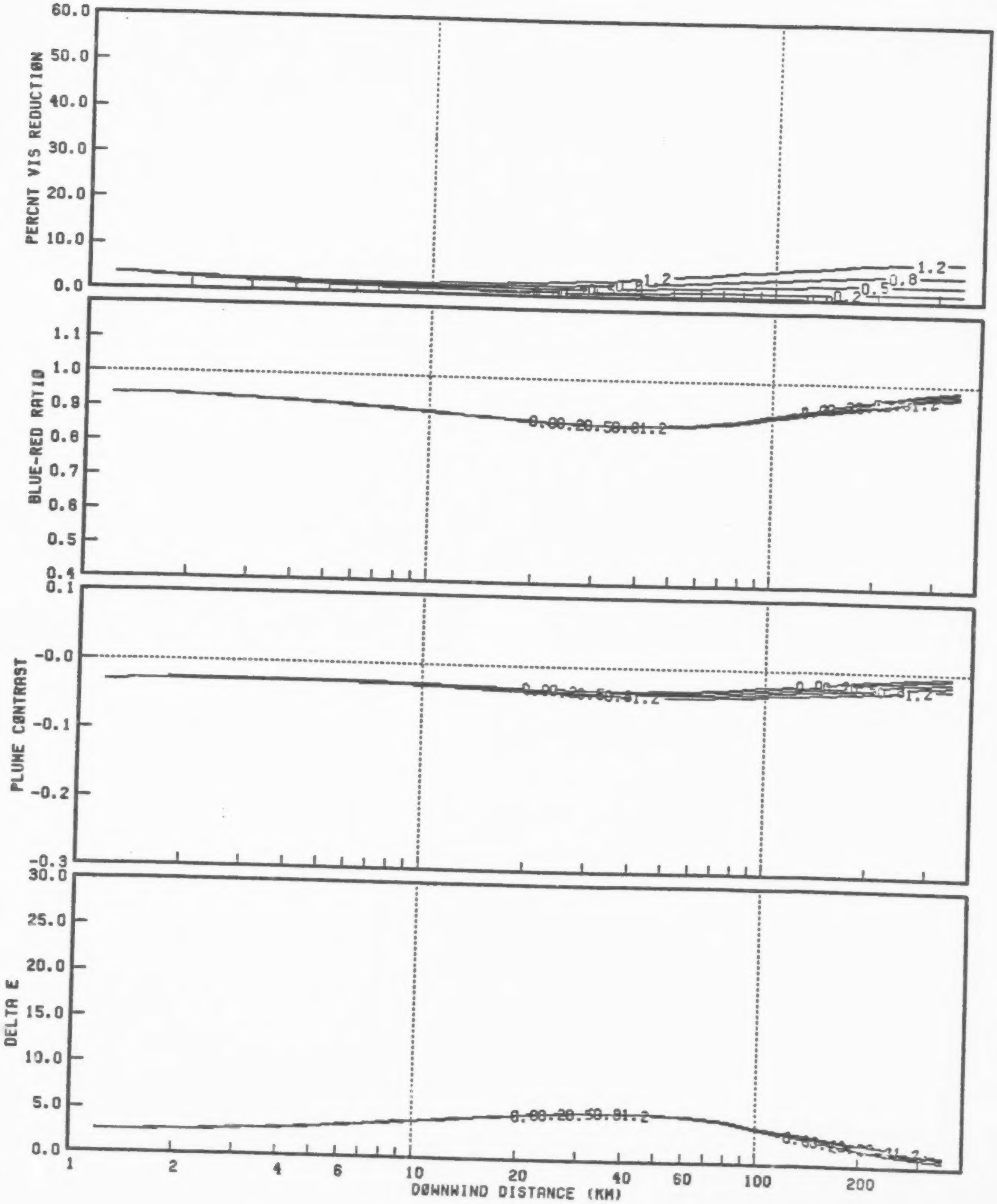
(a) Pasquill Stability C

FIGURE A-3. EFFECT OF $SO_2$ EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 500 MWe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. $SO_2$ emission rates in pounds per million Btu are indicated.



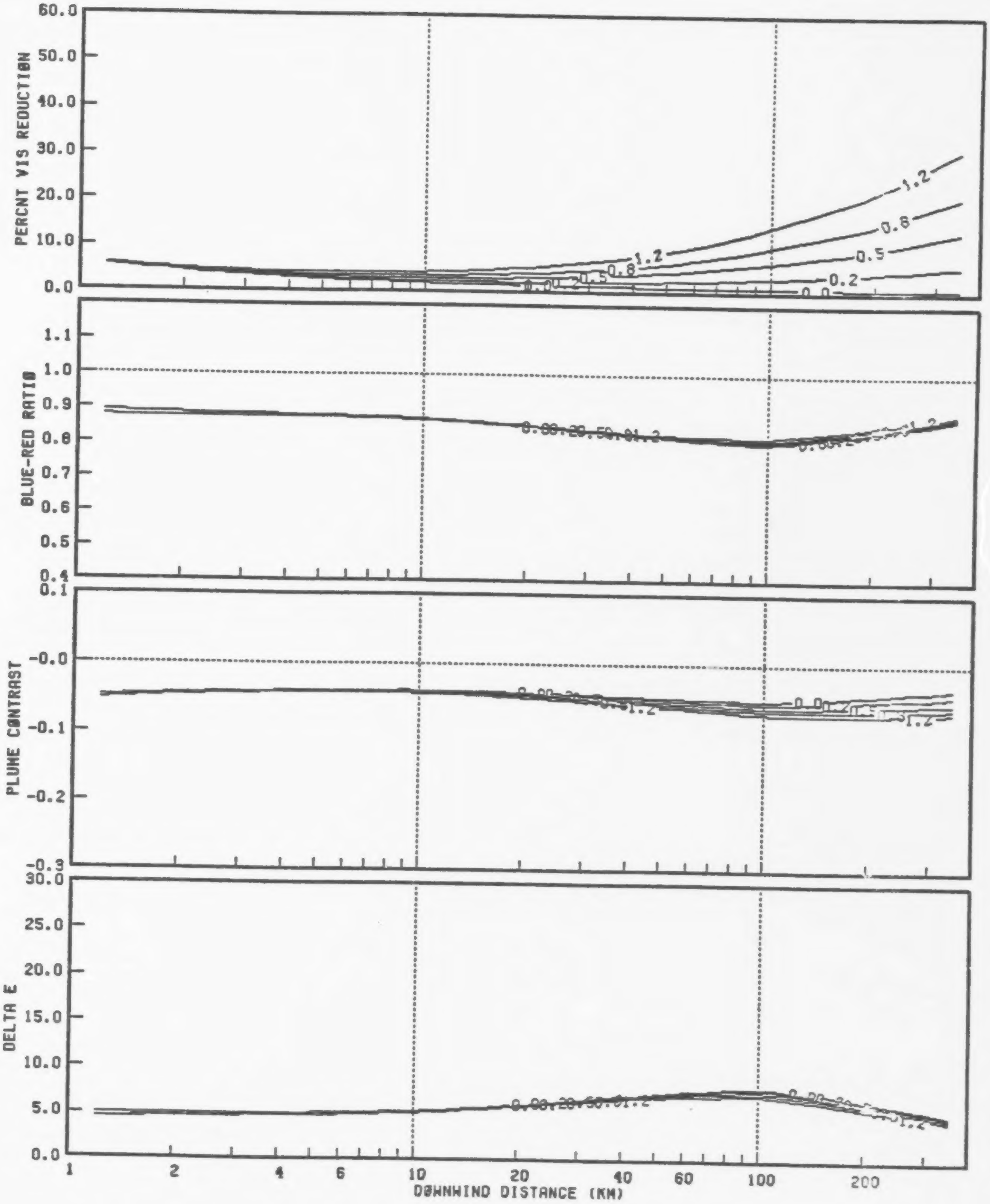
(b) Pasquill Stability D

FIGURE A-3 (Continued)



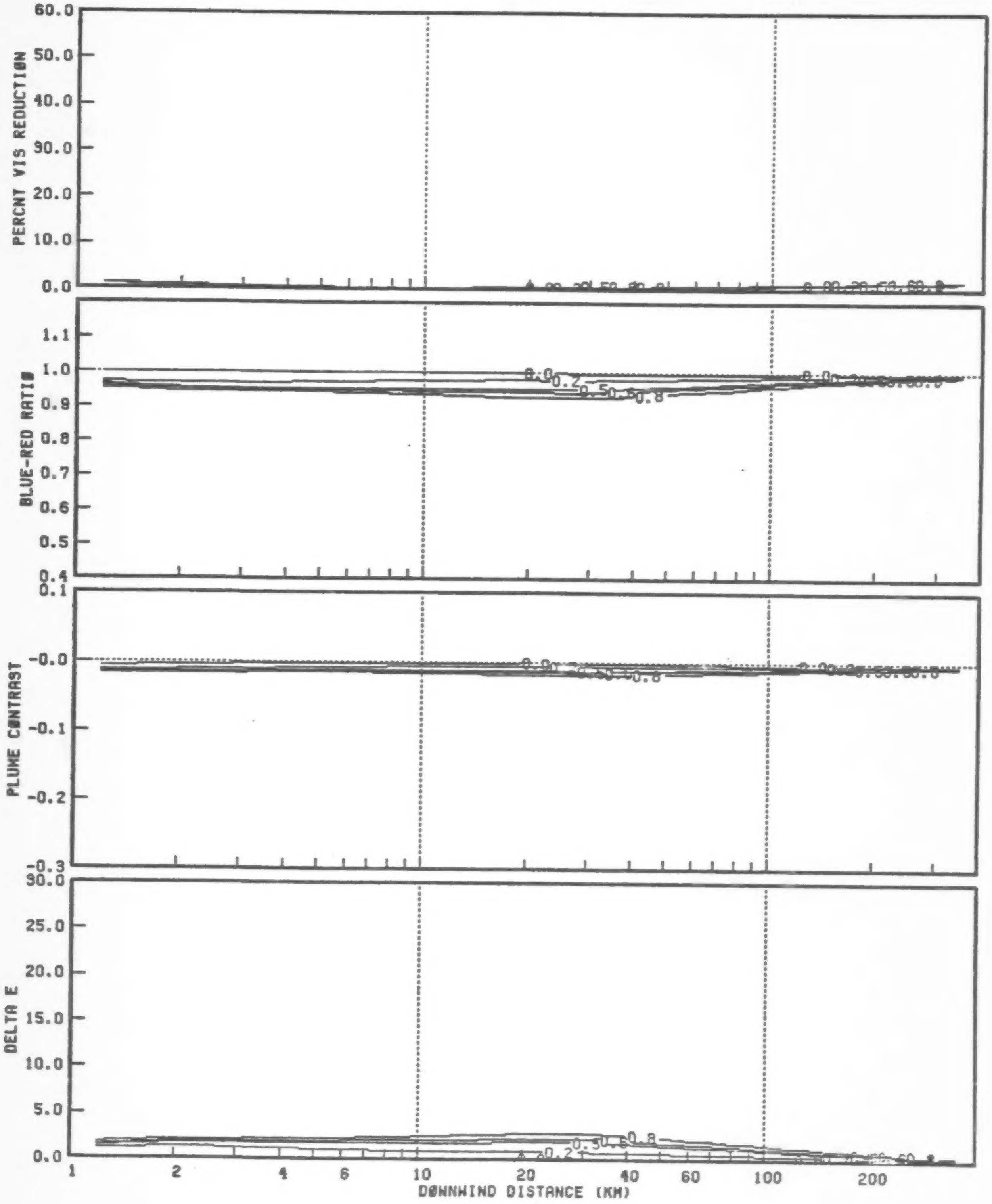
(c) Pasquill Stability E

FIGURE A-3 (Continued)



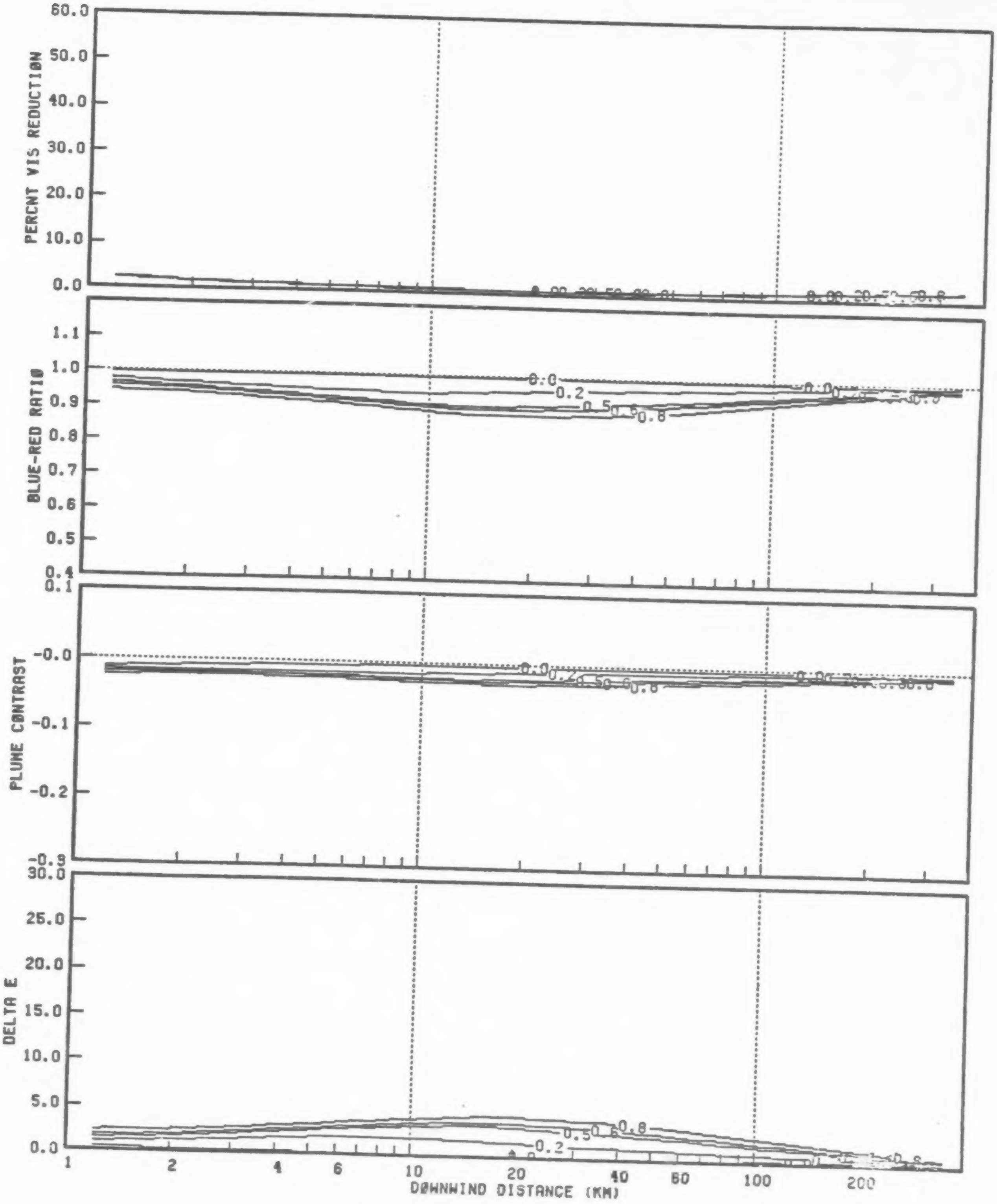
(d) Pasquill Stability F

FIGURE A-3 (Concluded)



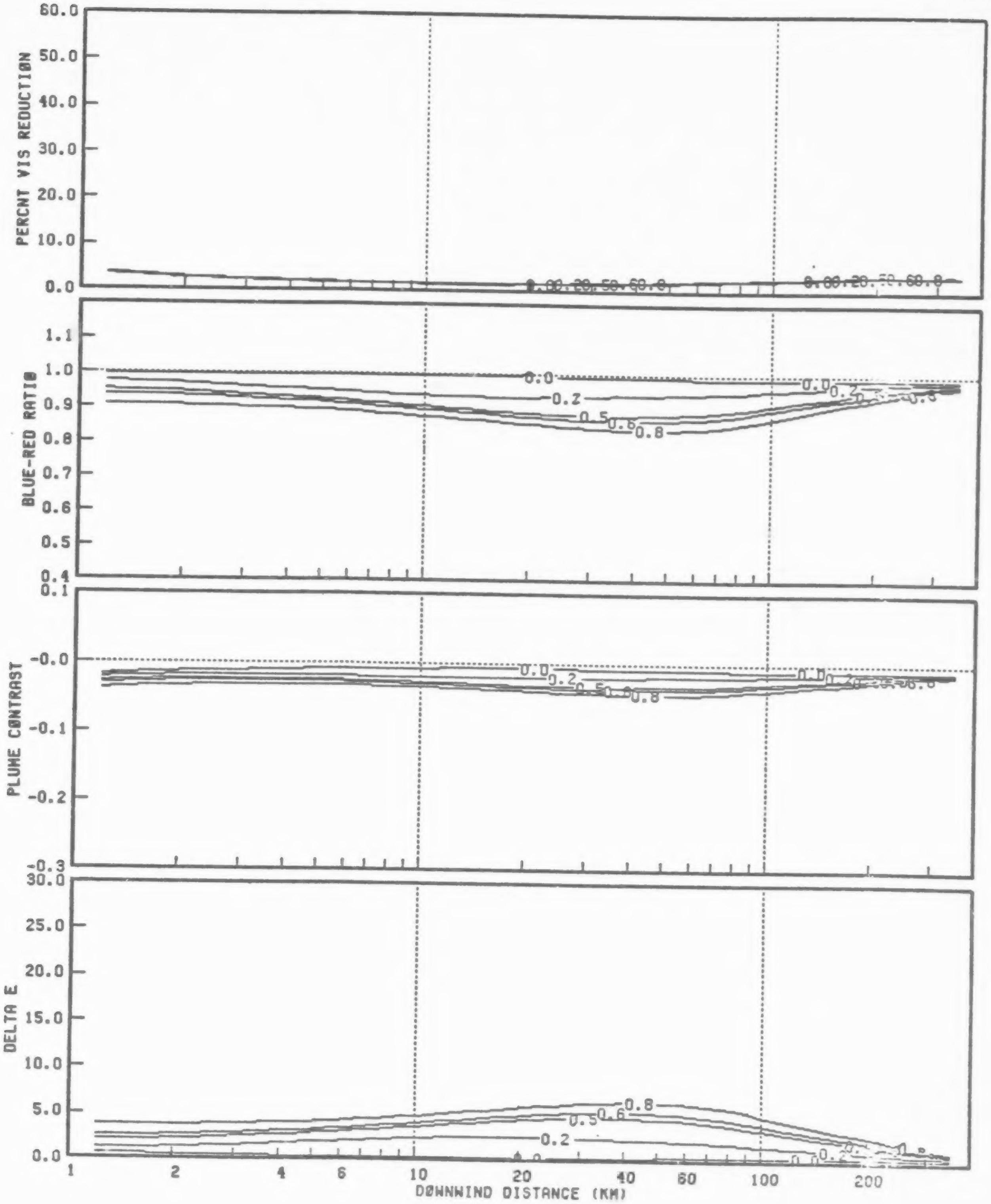
(a) Pasquill Stability C

FIGURE A-4. EFFECT OF $NO_x$ EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 500 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. $NO_x$ emission rates in pounds per million Btu are indicated.



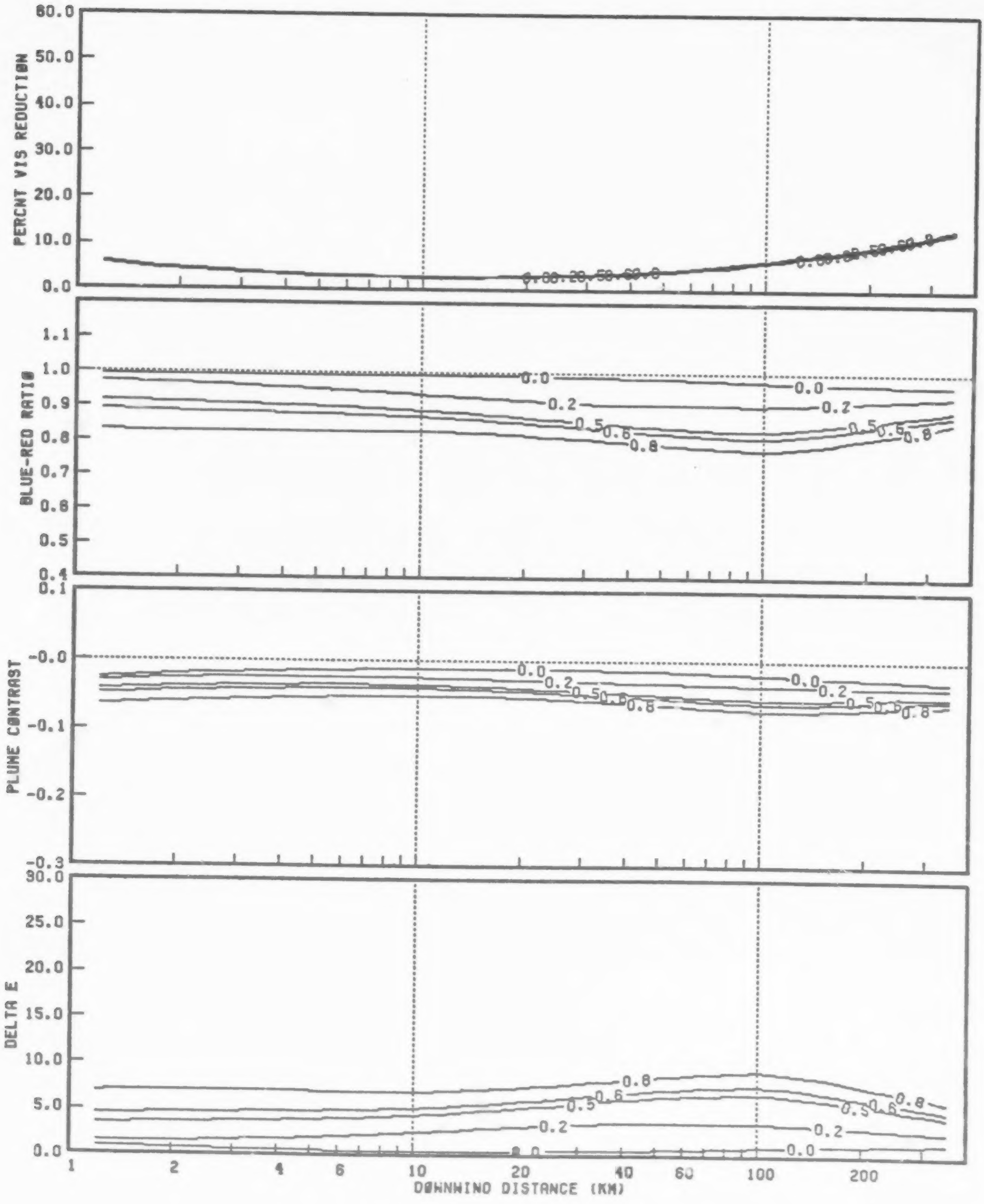
(b) Pasquill Stability D

FIGURE A-4 (Continued)



(c) Pasquill Stability E

FIGURE A-4 (Continued)

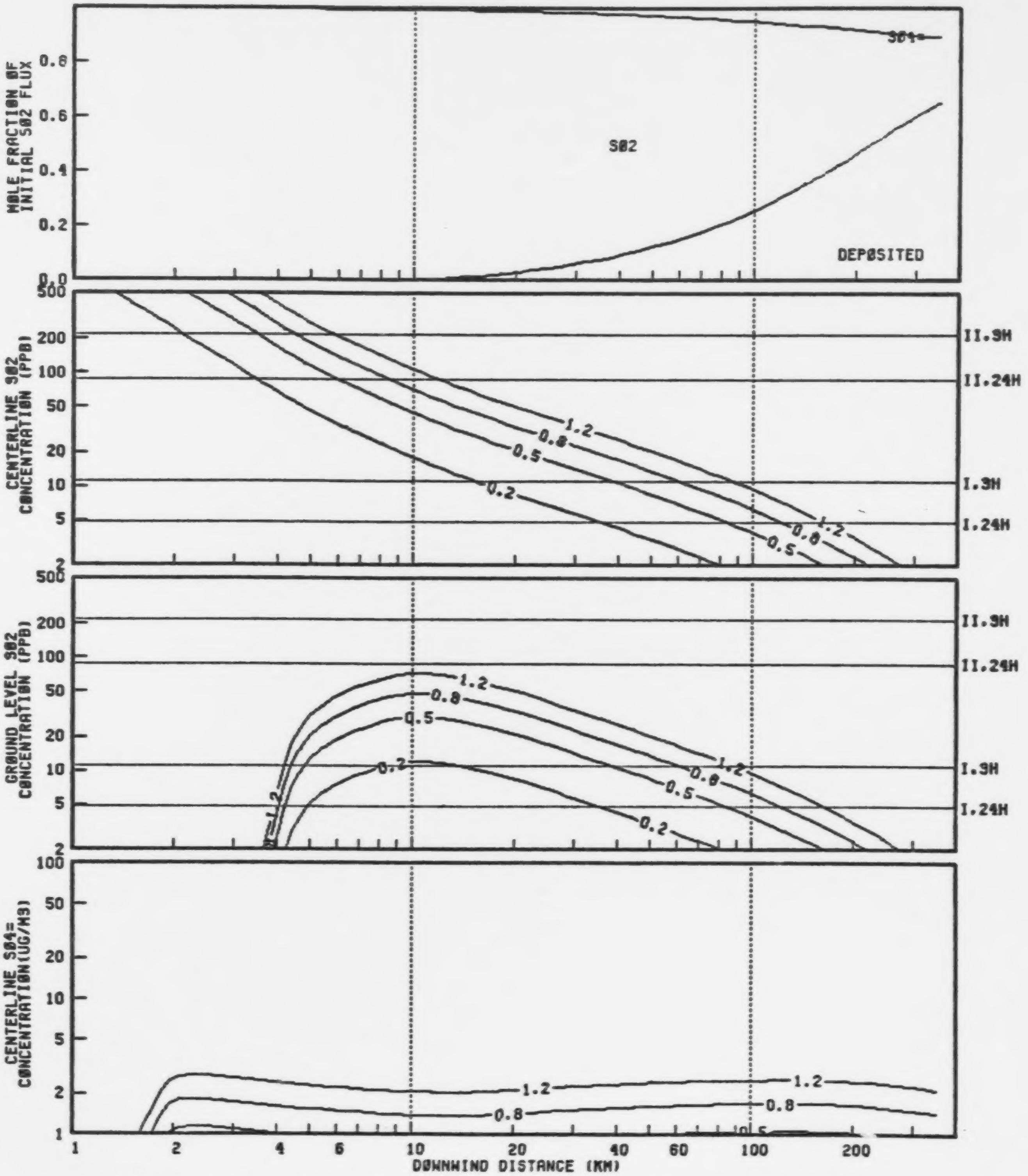


(d) Pasquill Stability F

FIGURE A-4 (Concluded)

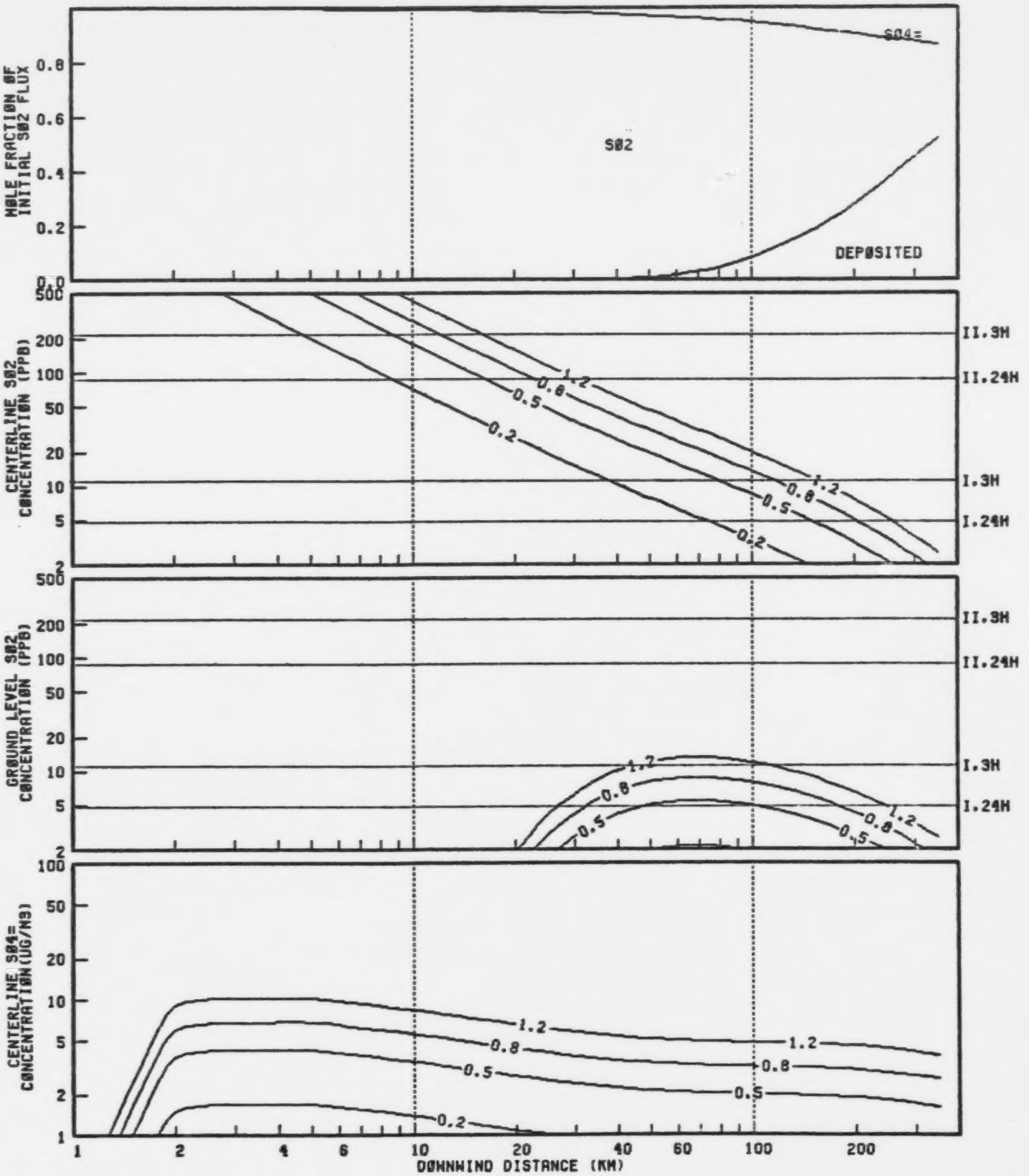
# APPENDIX B

# 1000 MWE POWER PLANT IMPACTS



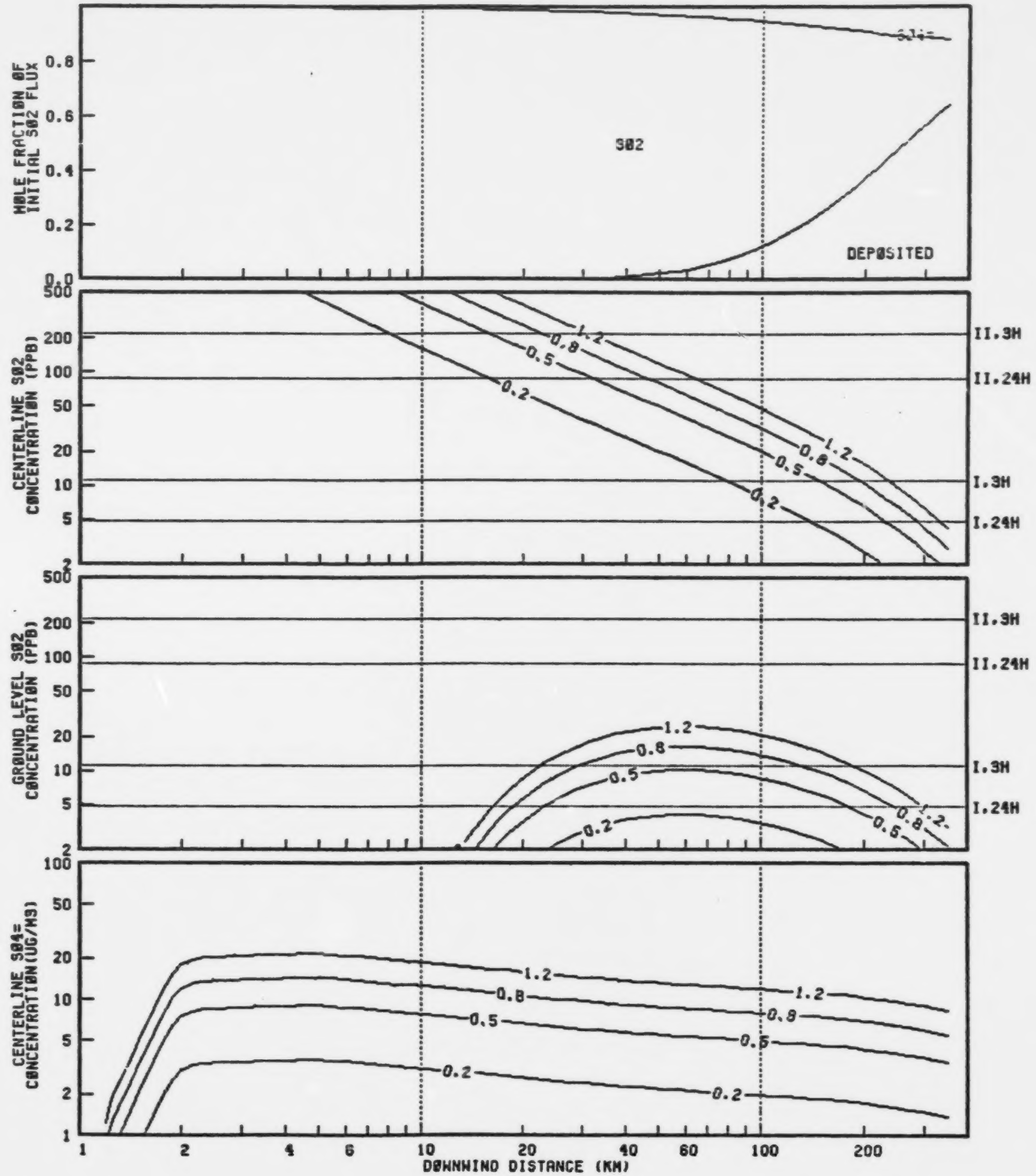
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE B-1. EFFECT OF $SO_2$ EMISSION RATES ON $SO_x$ FLUXES AND CONCENTRATIONS DOWNWIND OF A 1000 Mwe COAL-FIRED POWER PLANT. $SO_2$ emission rates in pounds per million Btu are indicated.



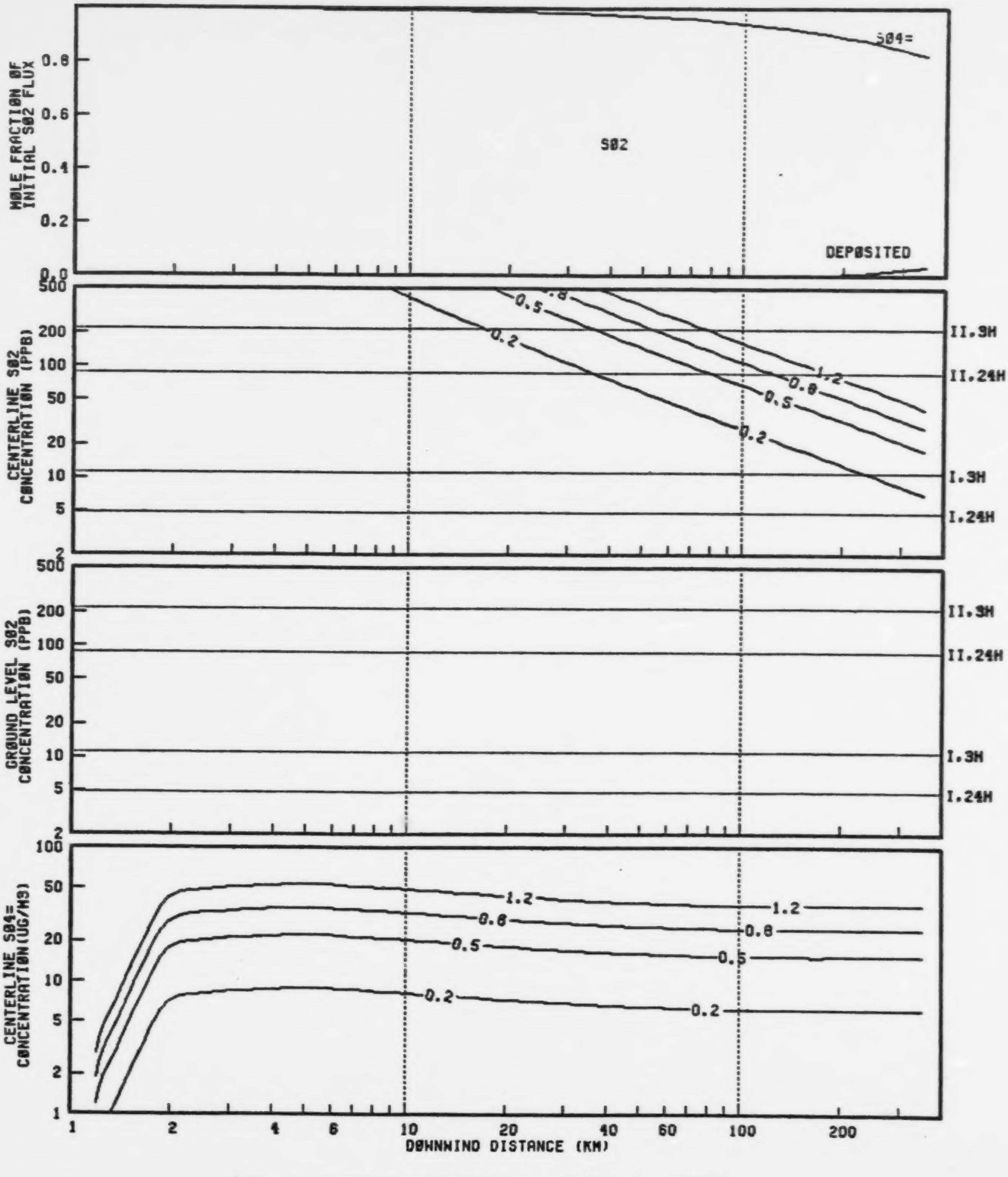
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE B-1 (Continued)



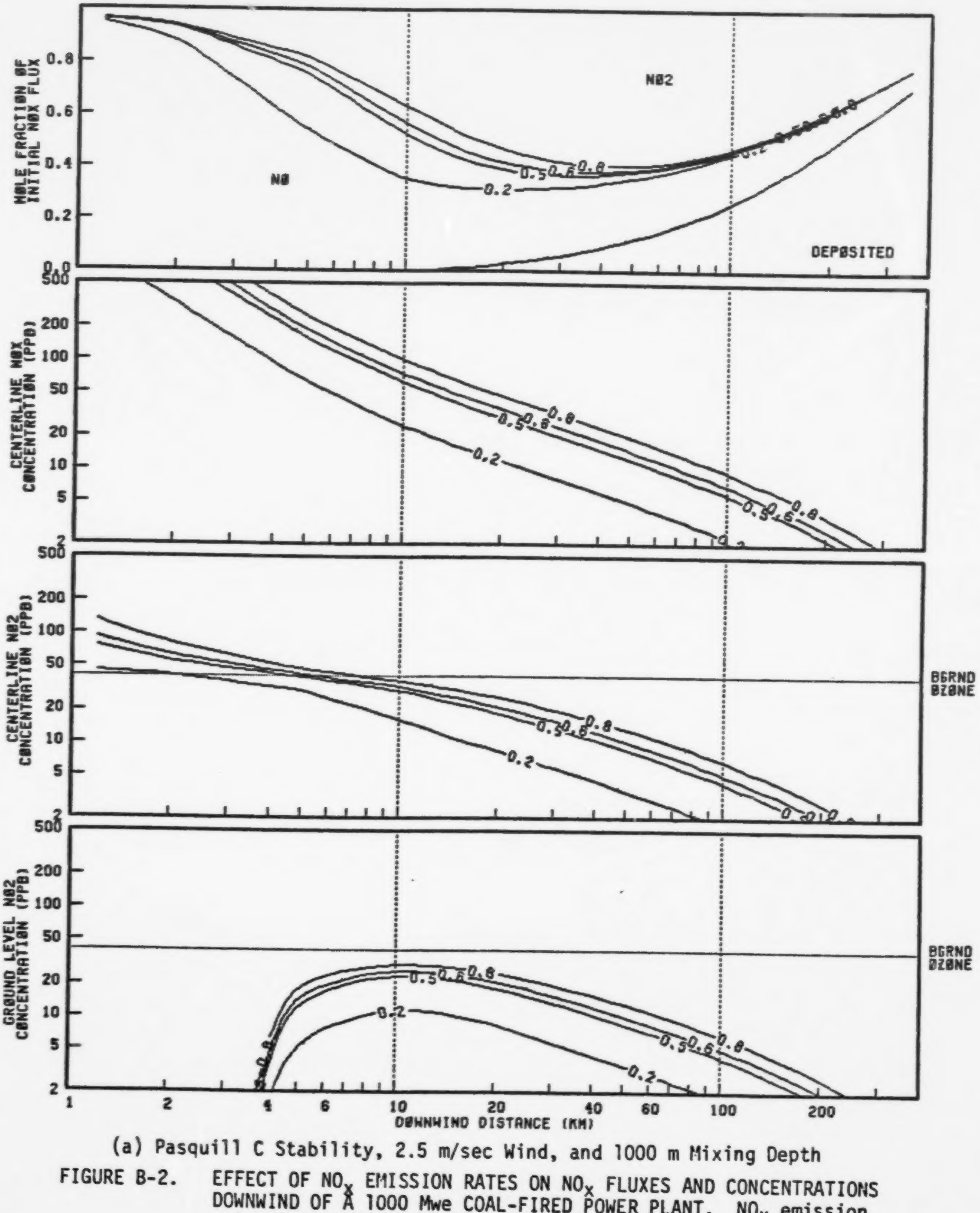
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE B-1 (Continued)



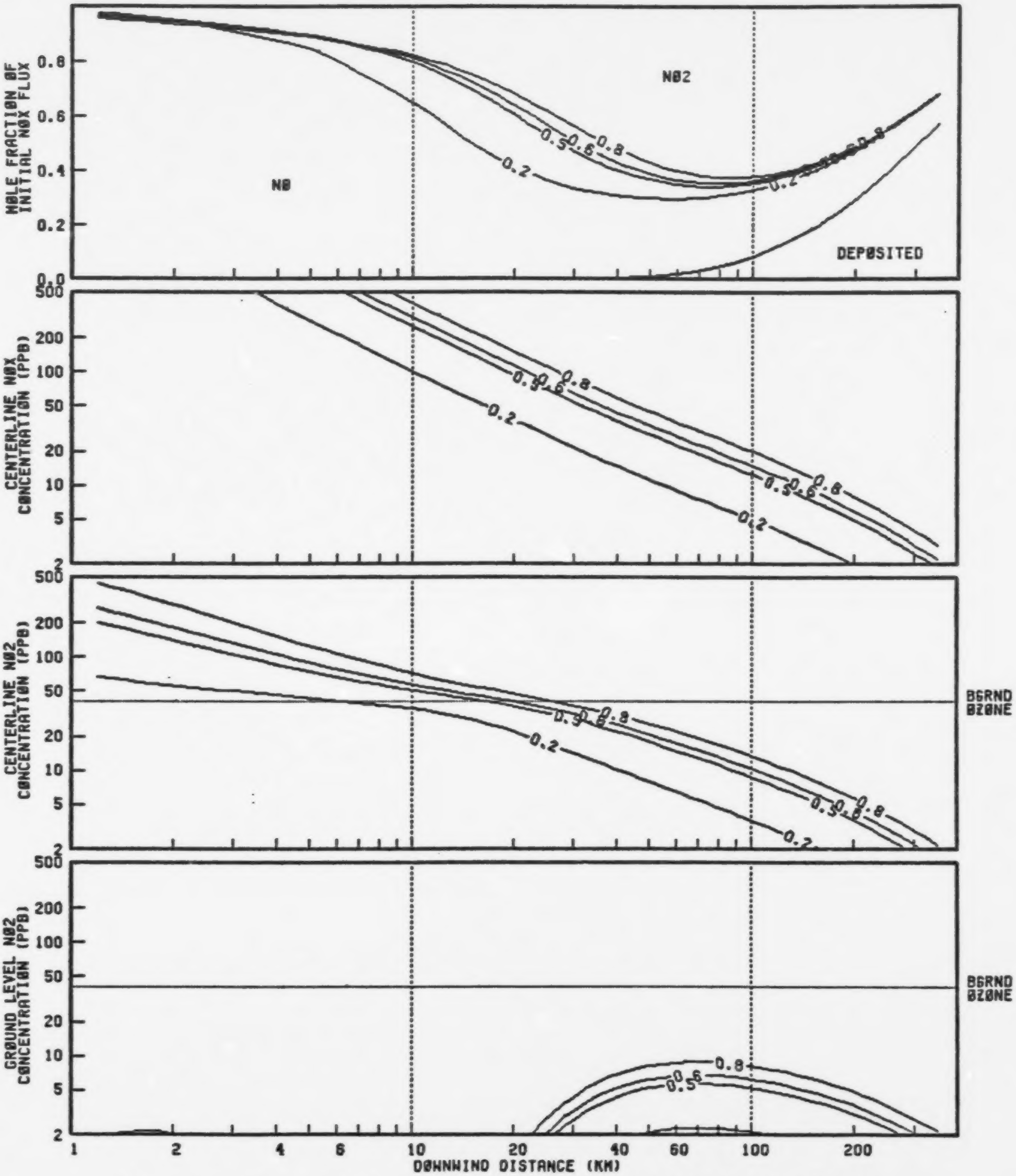
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE B-1 (Concluded)



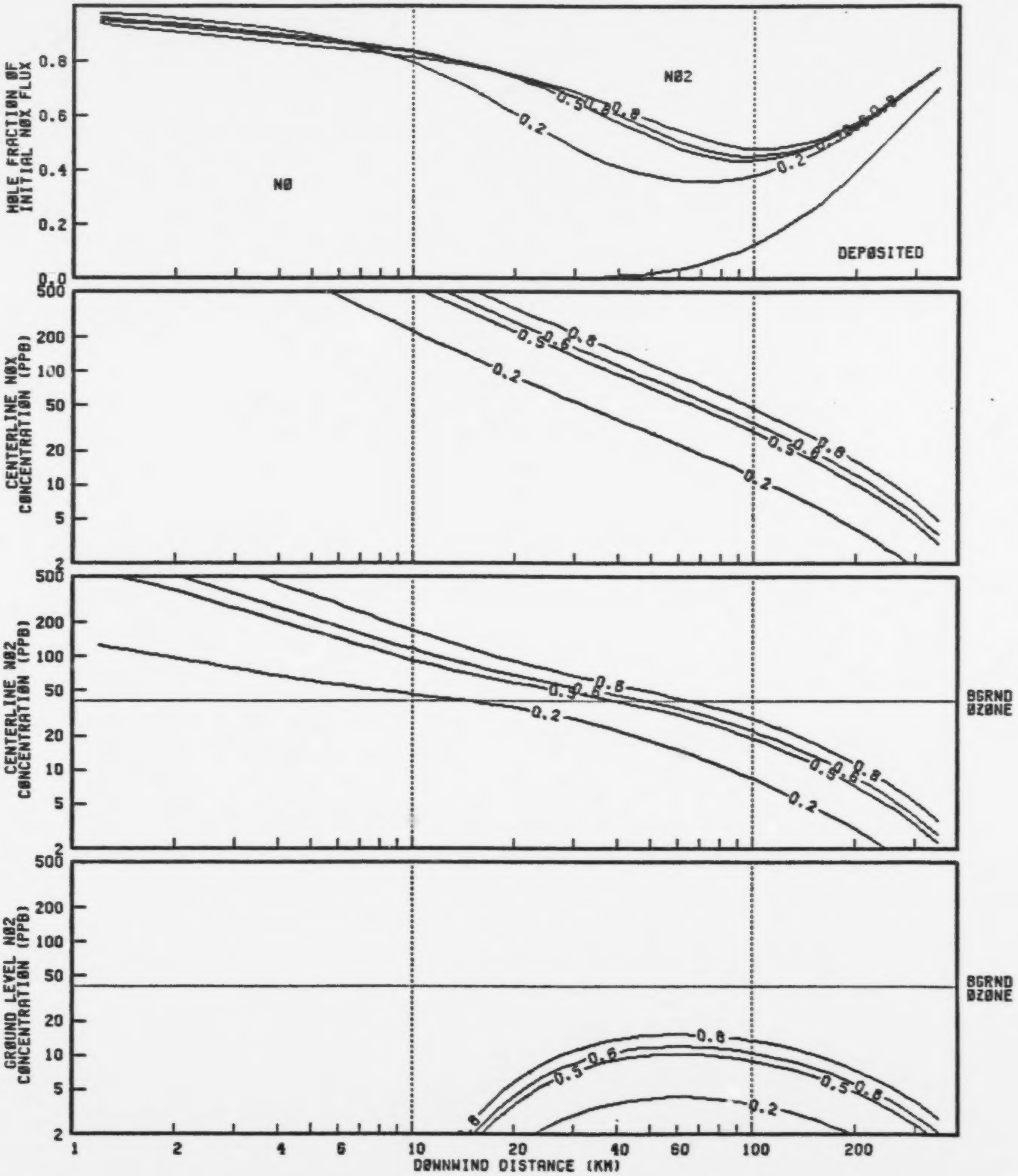
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE B-2. EFFECT OF $NO_x$ EMISSION RATES ON $NO_x$ FLUXES AND CONCENTRATIONS DOWNWIND OF A 1000 Mwe COAL-FIRED POWER PLANT. $NO_x$ emission rates in pounds per million Btu are indicated.



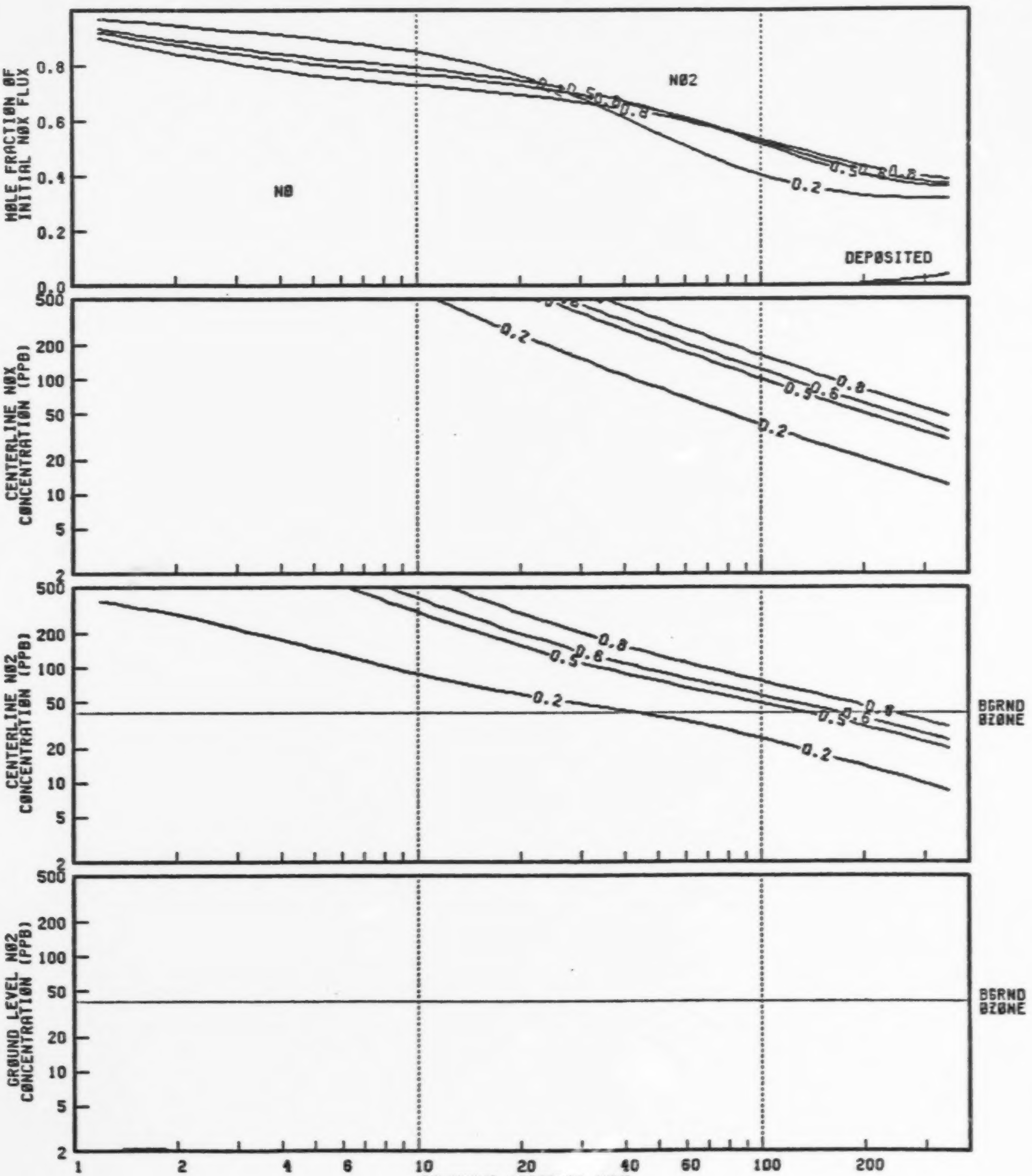
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE B-2 (Continued)



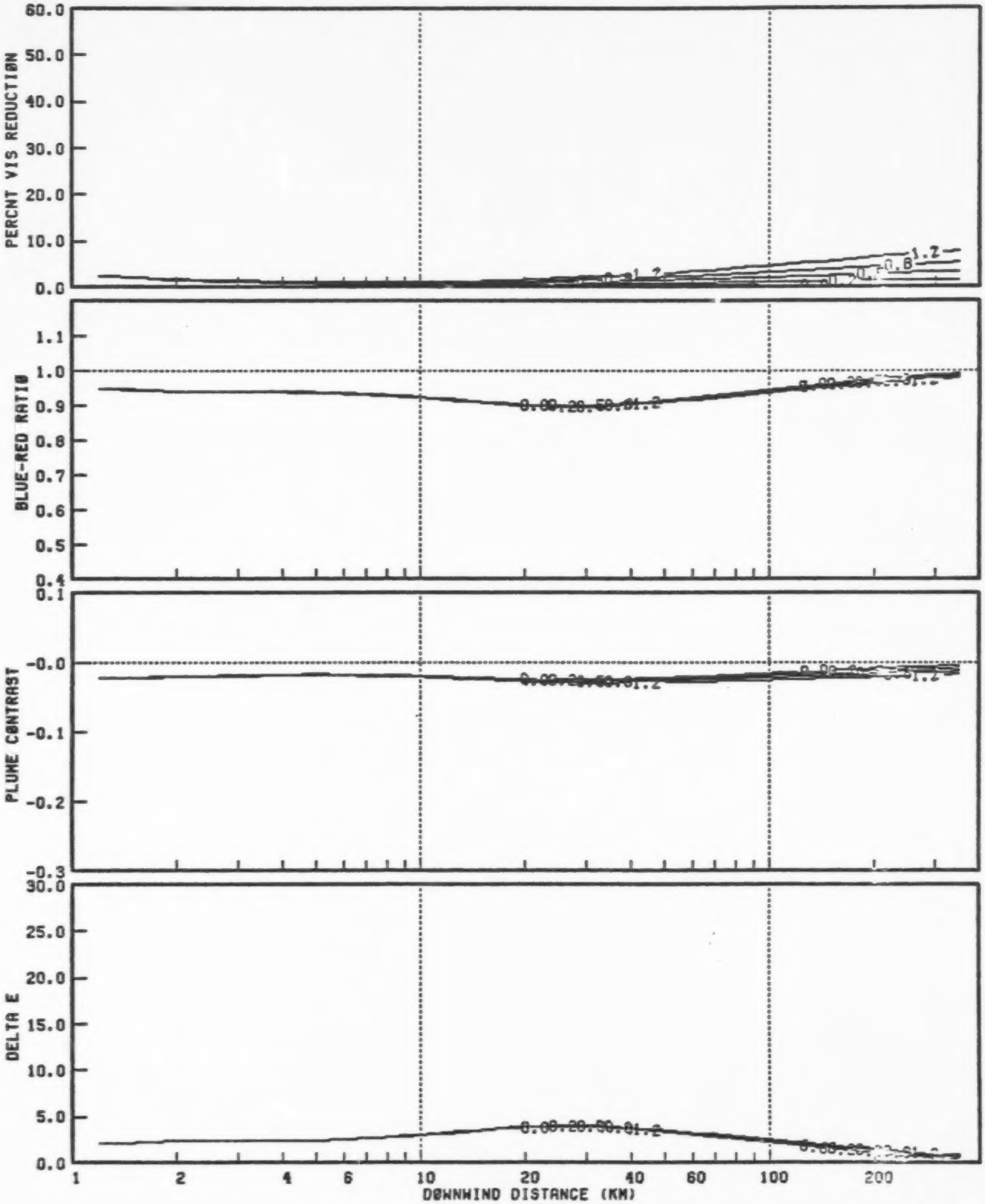
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE B-2 (Continued)



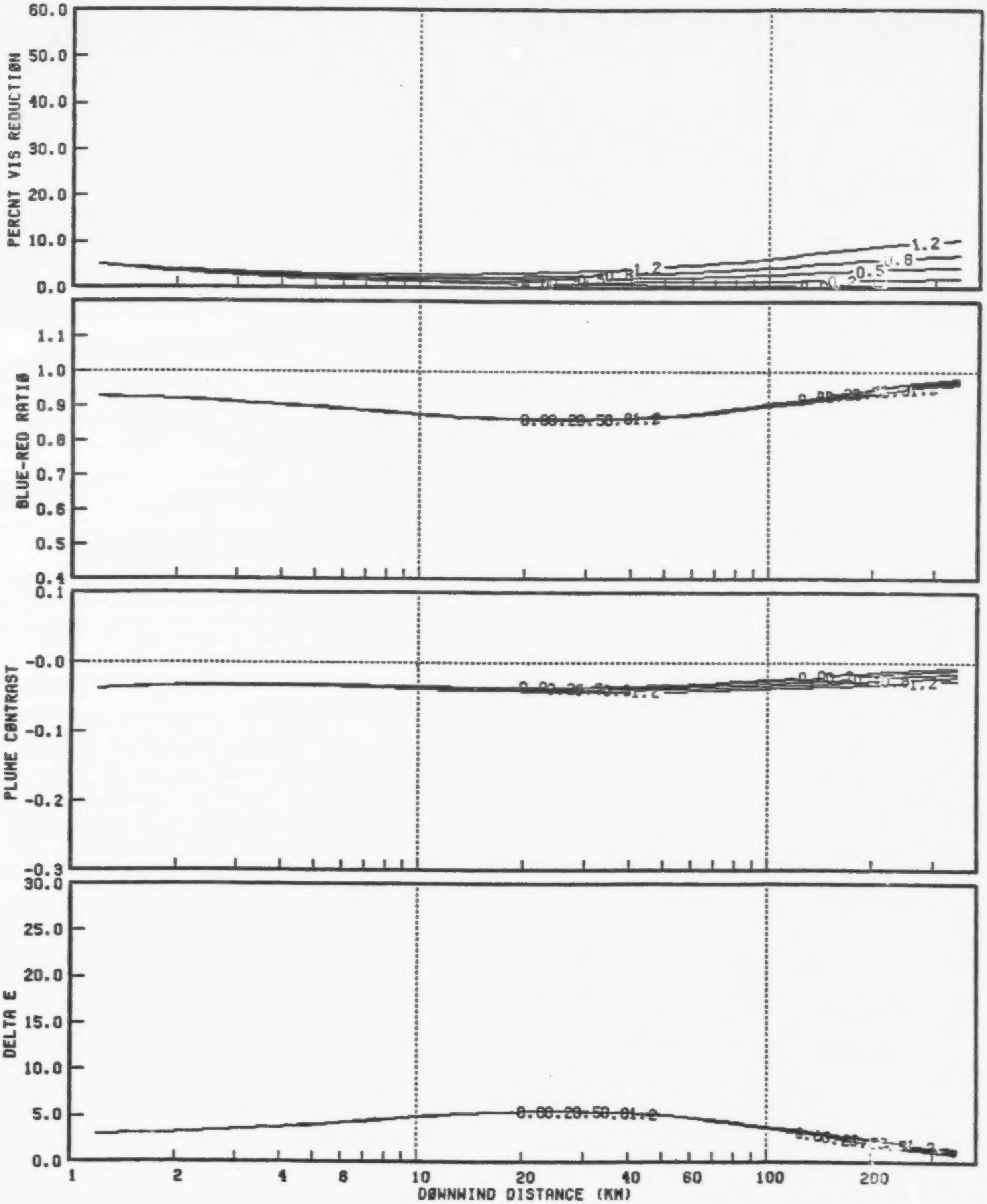
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE B-2 (Concluded)



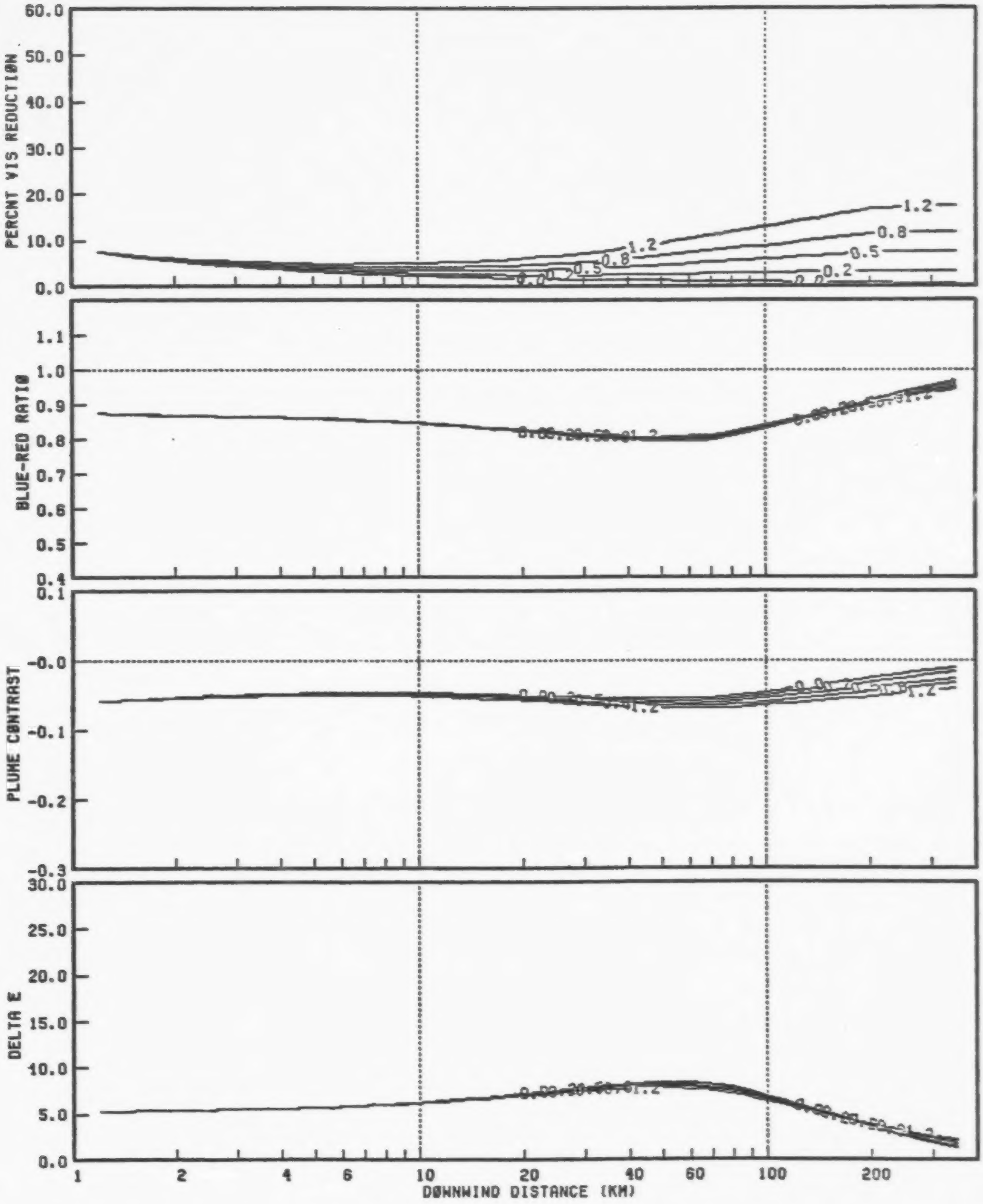
(a) Pasquill Stability C

FIGURE B-3. EFFECT OF $SO_2$ EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 1000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. $SO_2$ emission rates in pounds per million Btu are indicated.



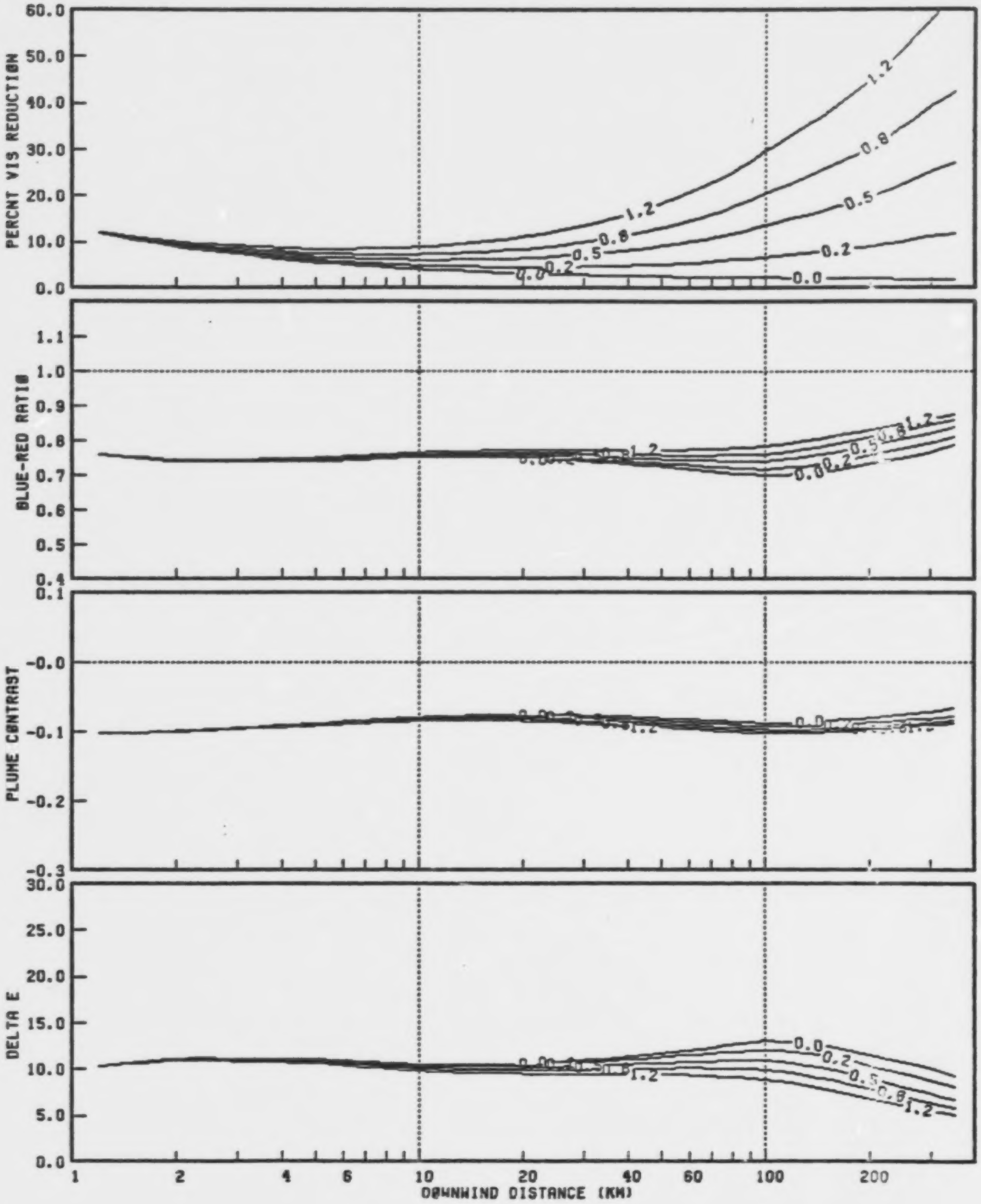
(b) Pasquill Stability D

FIGURE B-3 (Continued)



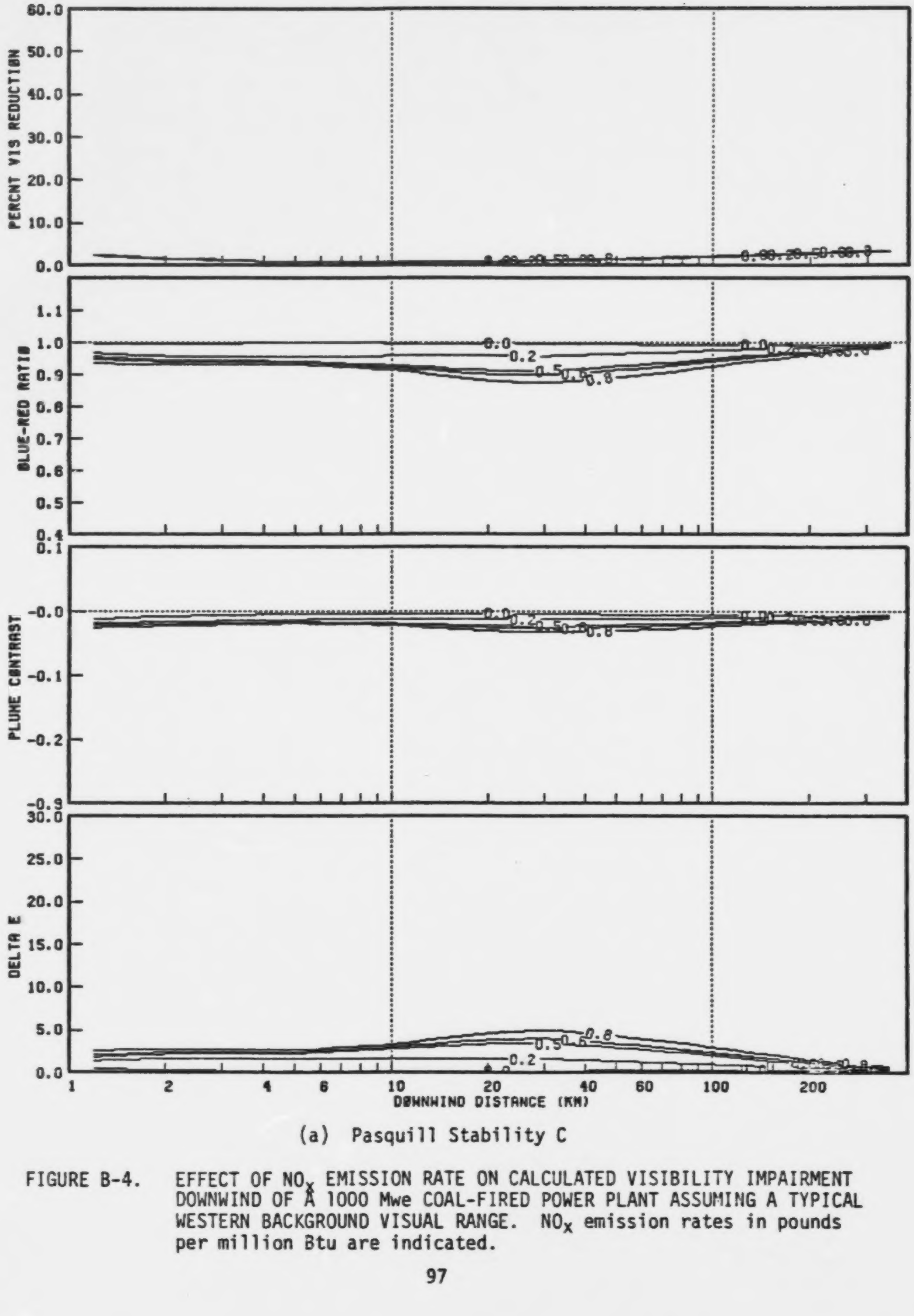
(c) Pasquill Stability E

FIGURE B-3 (Continued)



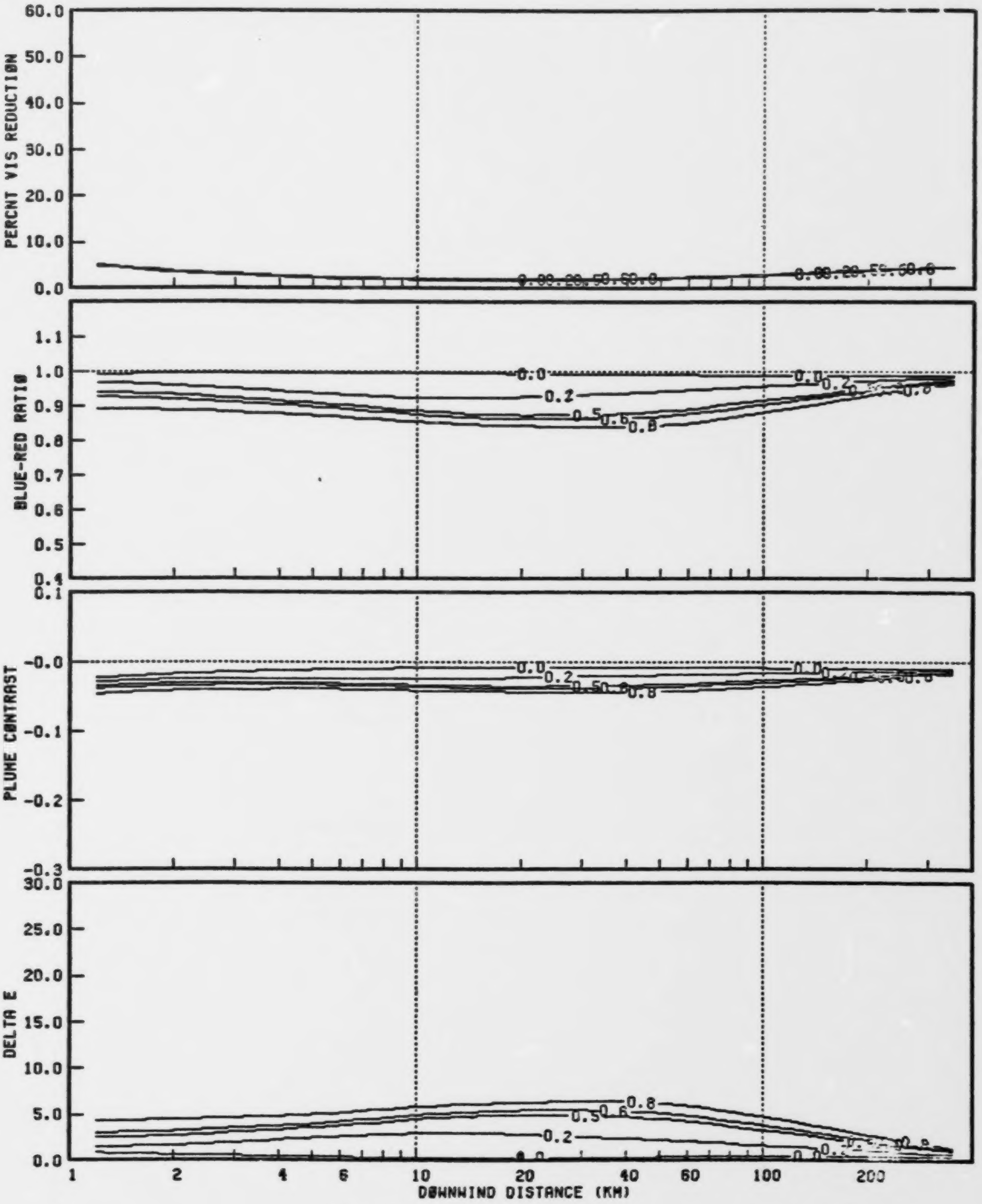
(d) Pasquill Stability F

FIGURE B-3 (Concluded)



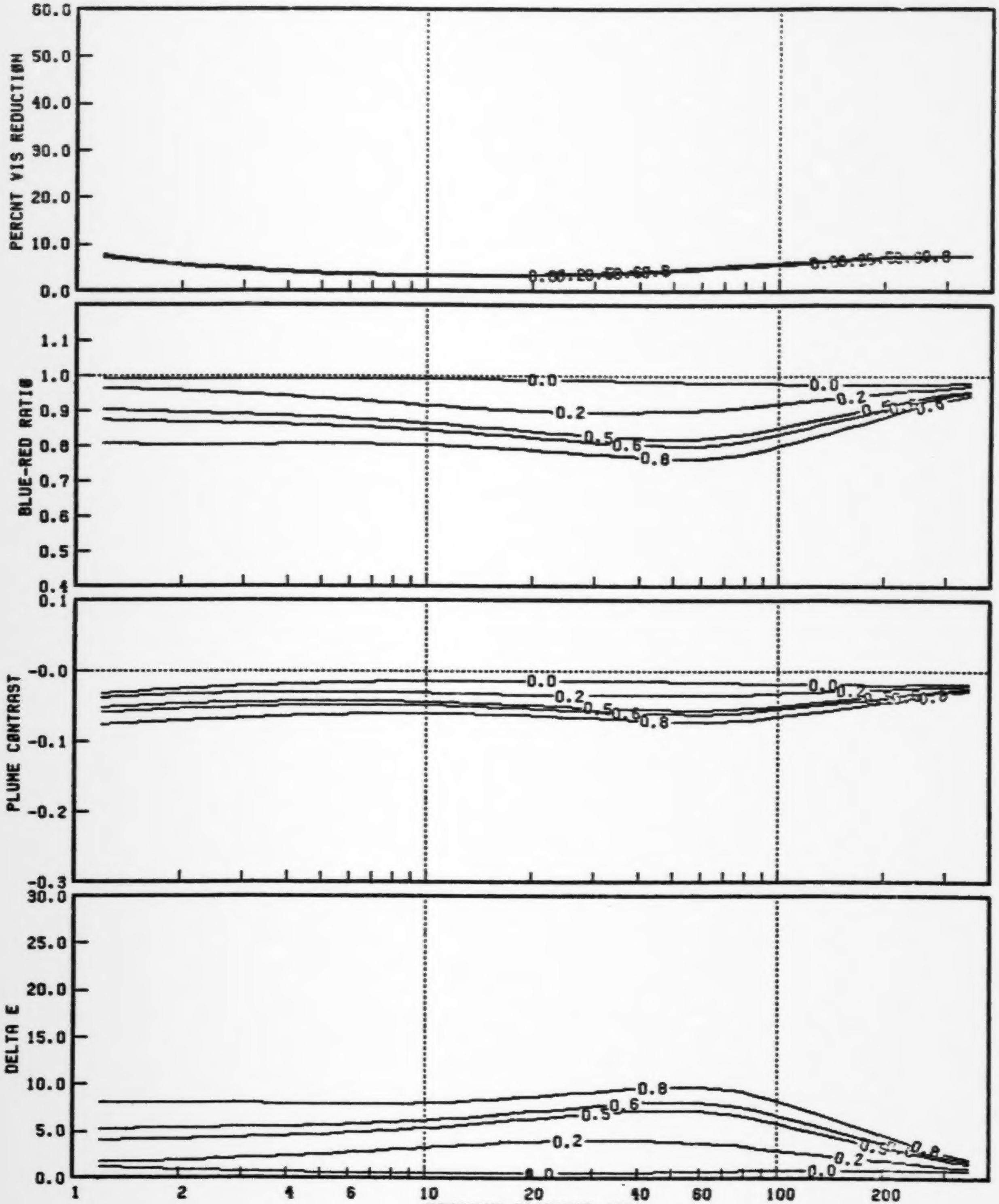
(a) Pasquill Stability C

FIGURE B-4. EFFECT OF $NO_x$ EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 1000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. $NO_x$ emission rates in pounds per million Btu are indicated.



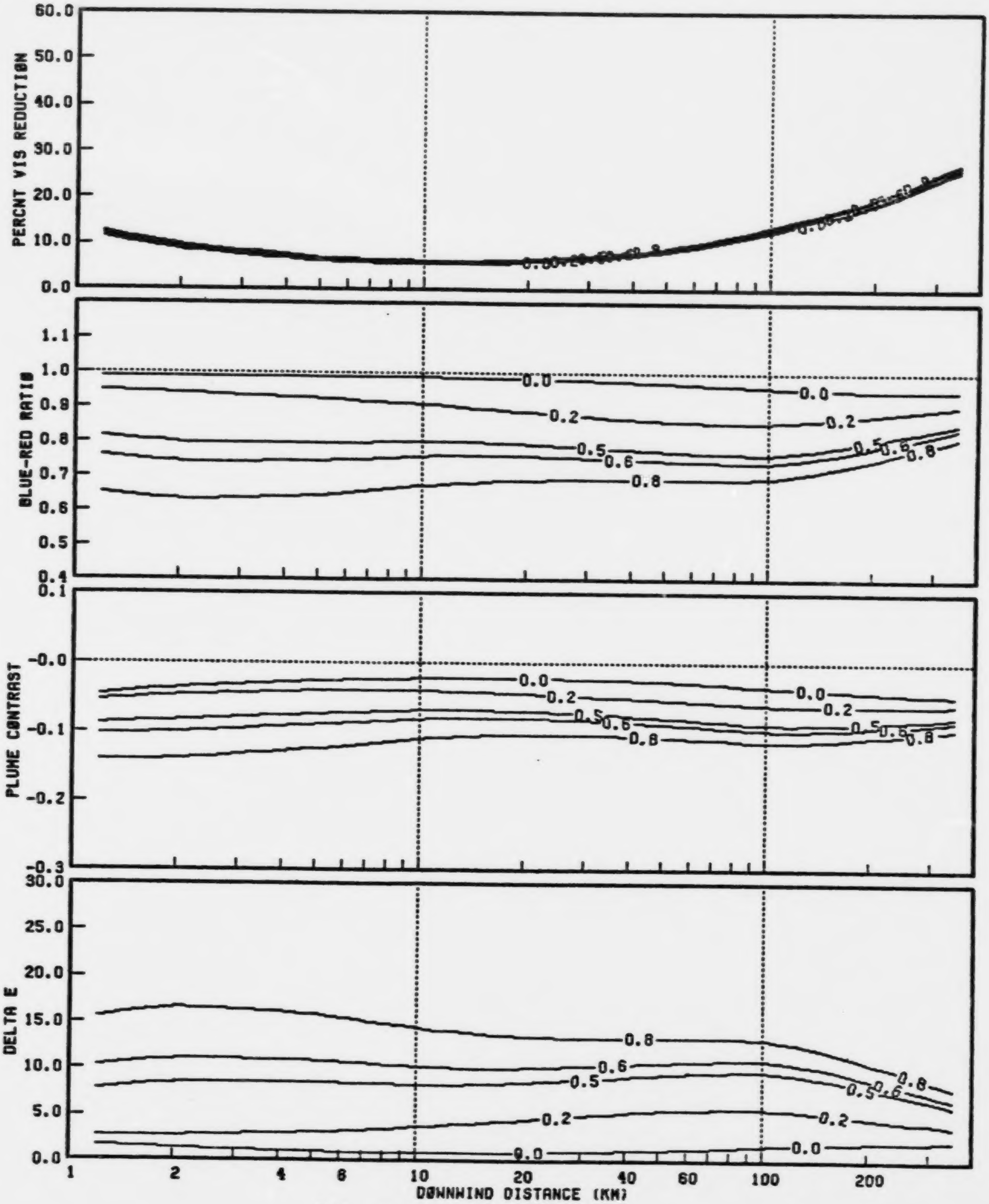
(b) Pasquill Stability D

FIGURE B-4 (Continued)



(c) Pasquill Stability E

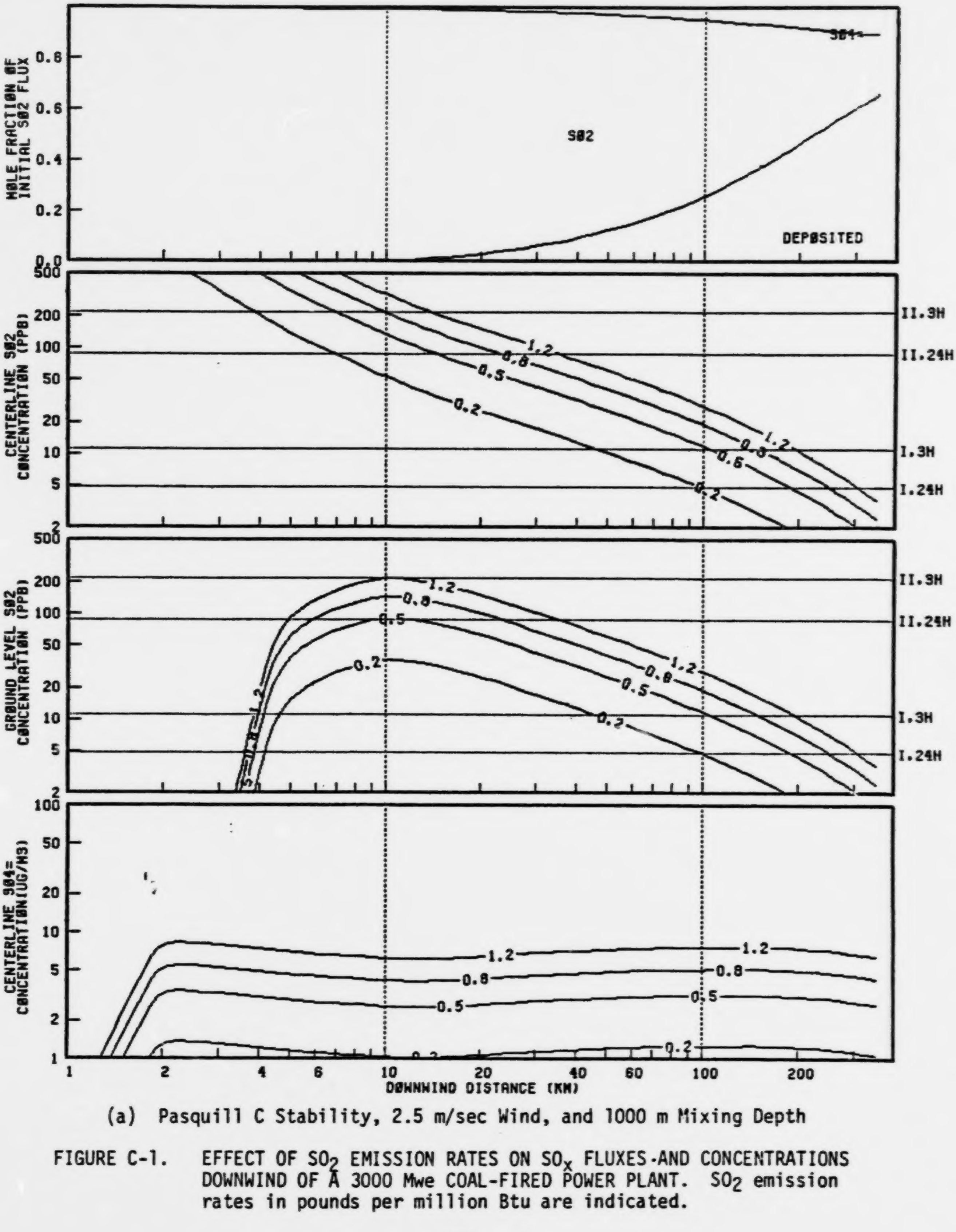
FIGURE B-4 (Continued)



(d) Pasquill Stability F

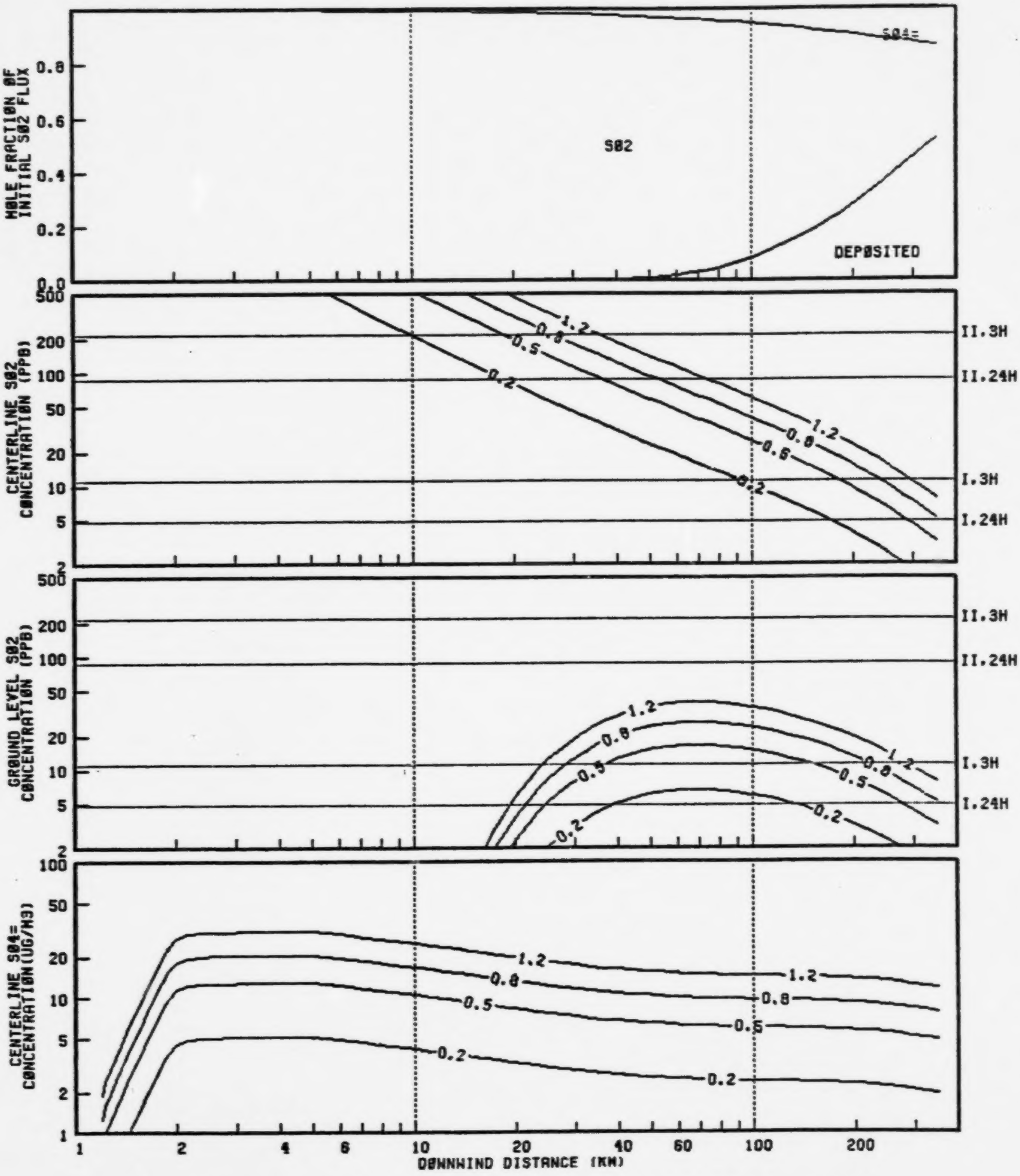
FIGURE B-4 (Concluded)

# APPENDIX C
# 3000 MWE POWER PLANT IMPACTS



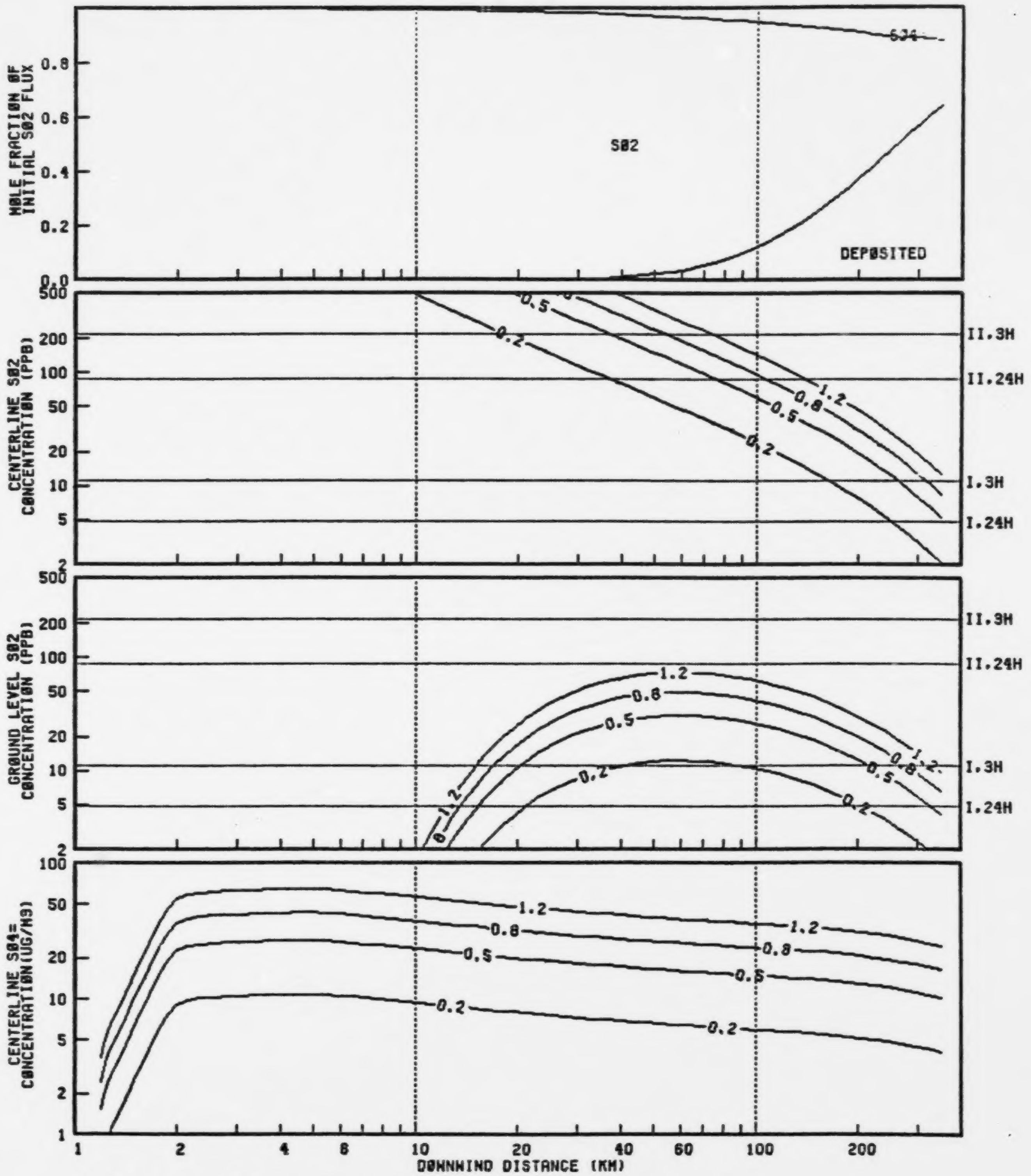
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE C-1. EFFECT OF $SO_2$ EMISSION RATES ON $SO_x$ FLUXES AND CONCENTRATIONS DOWNWIND OF A 3000 Mwe COAL-FIRED POWER PLANT. $SO_2$ emission rates in pounds per million Btu are indicated.



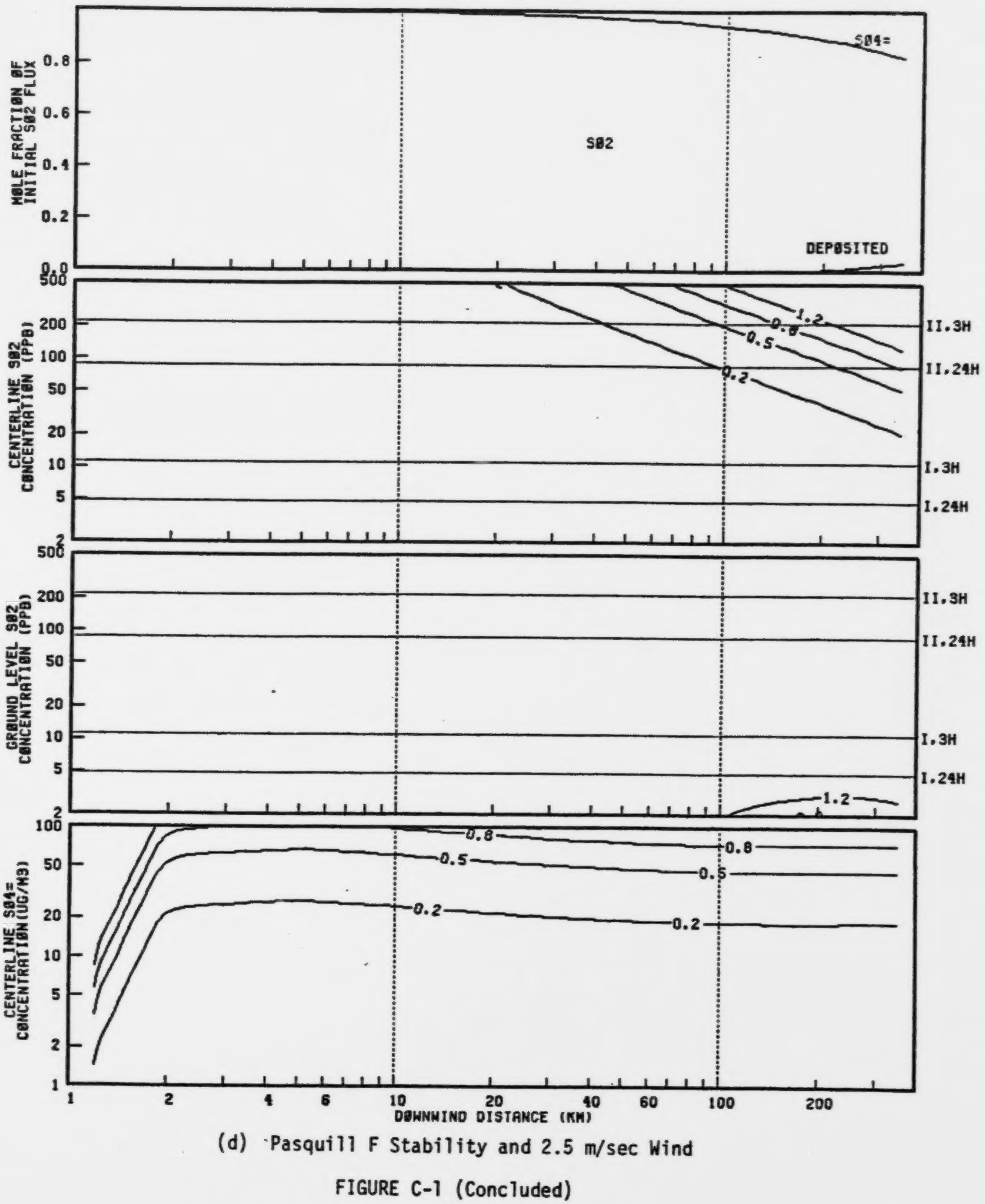
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE C-1 (Continued)



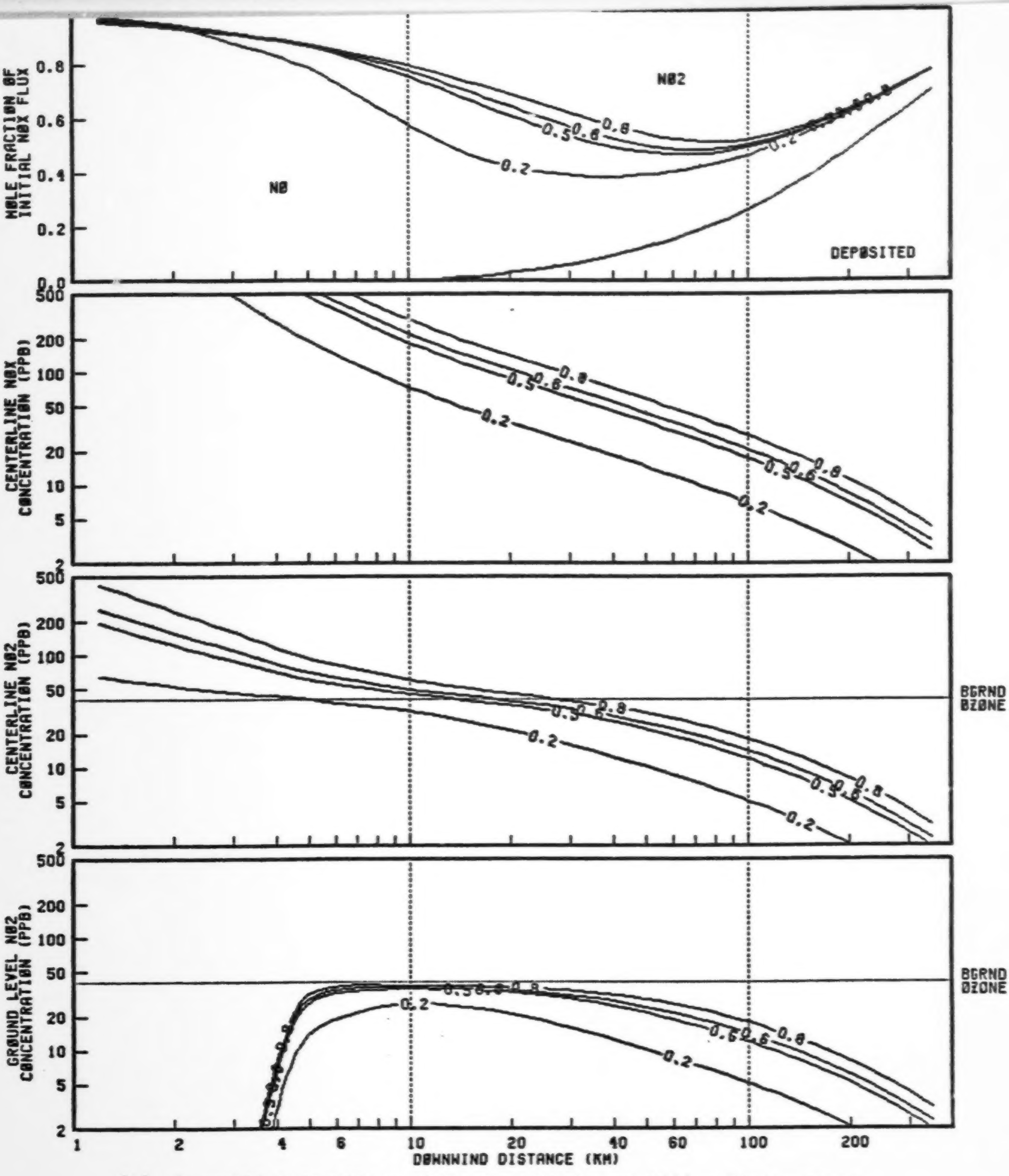
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE C-1 (Continued)



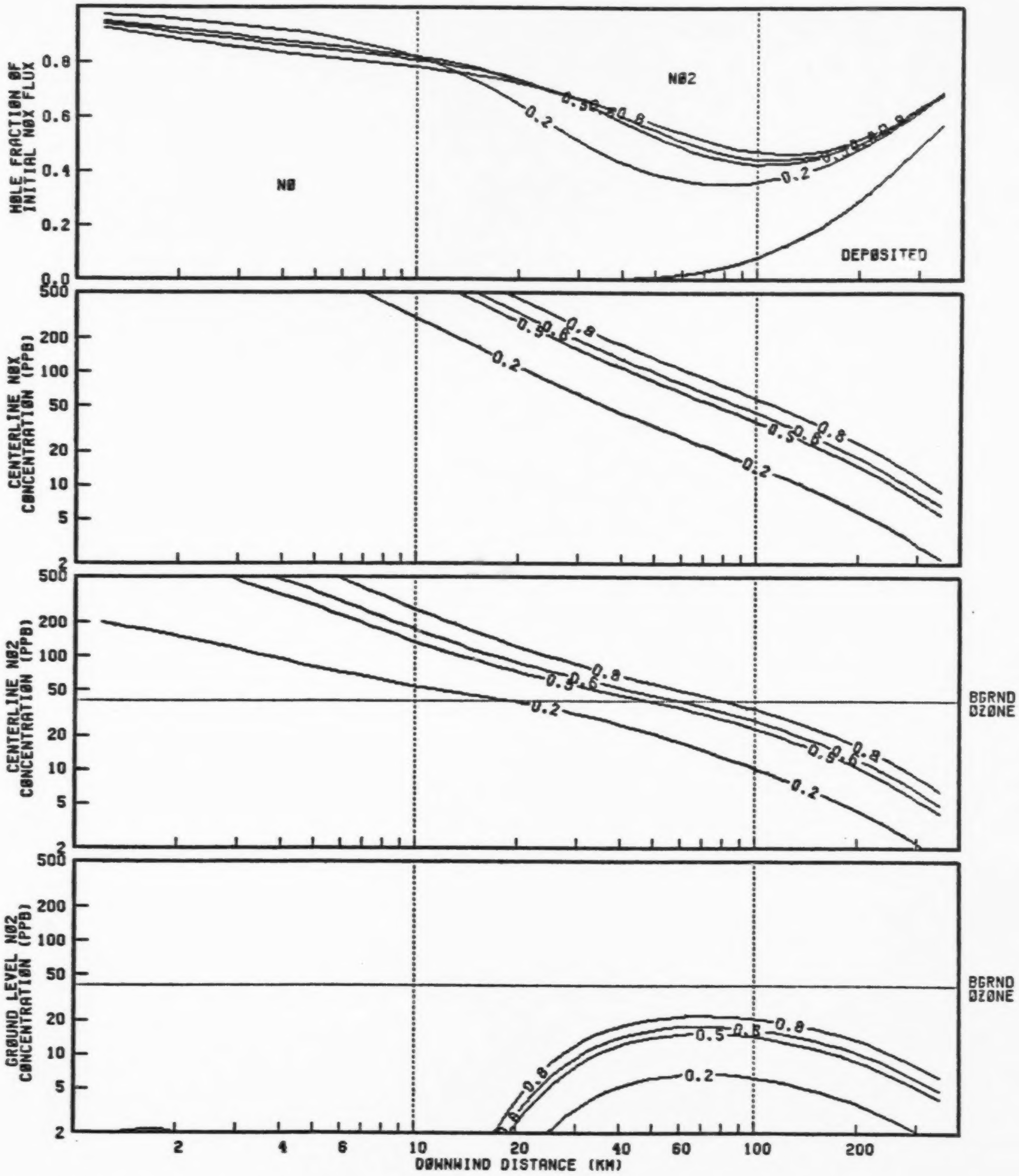
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE C-1 (Concluded)



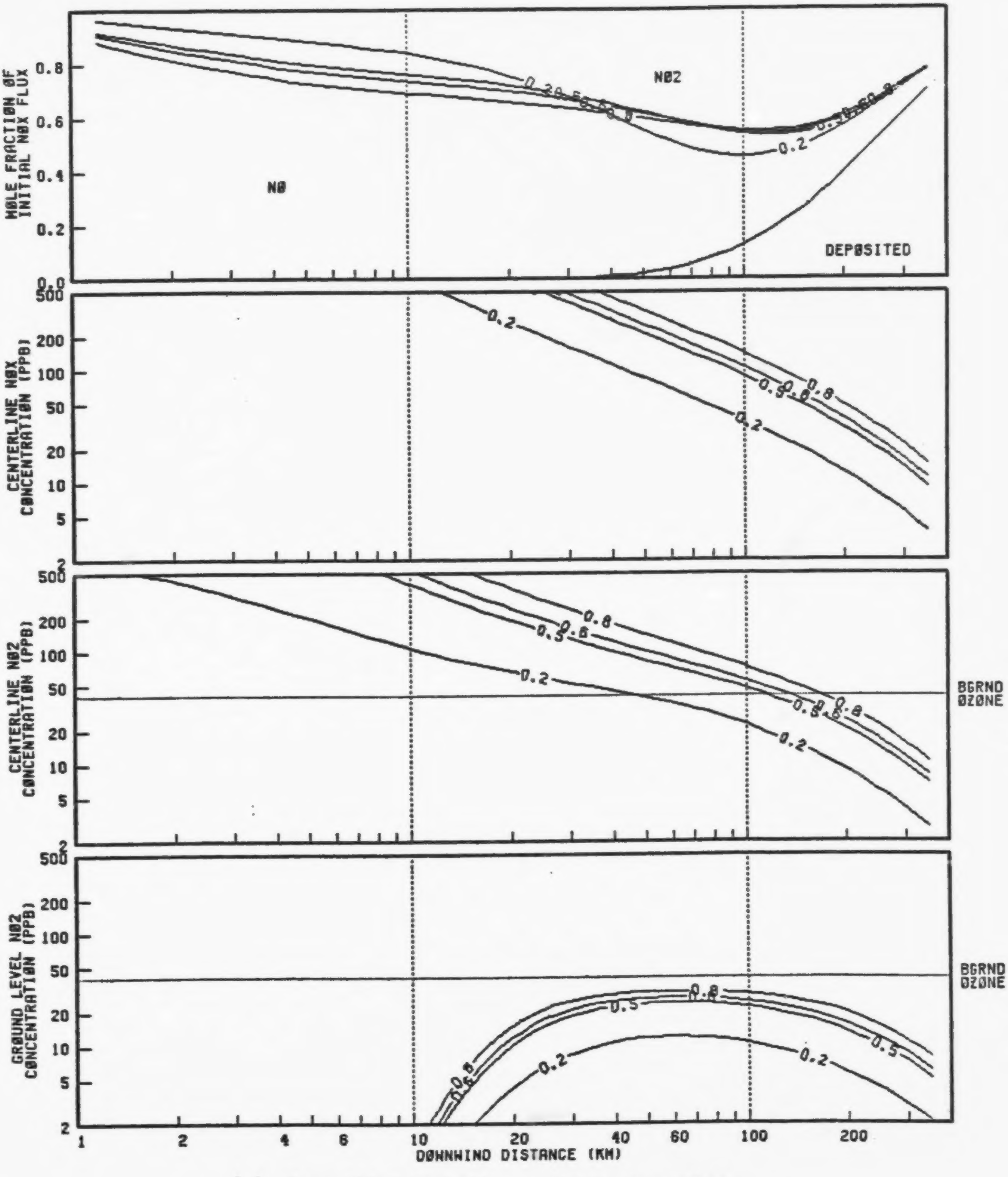
(a) Pasquill C Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE C-2. EFFECT OF $NO_x$ EMISSION RATES ON $NO_x$ FLUXES AND CONCENTRATIONS DOWNWIND OF A 3000 Mwe COAL-FIRED POWER PLANT. $NO_x$ emission rates in pounds per million Btu are indicated.



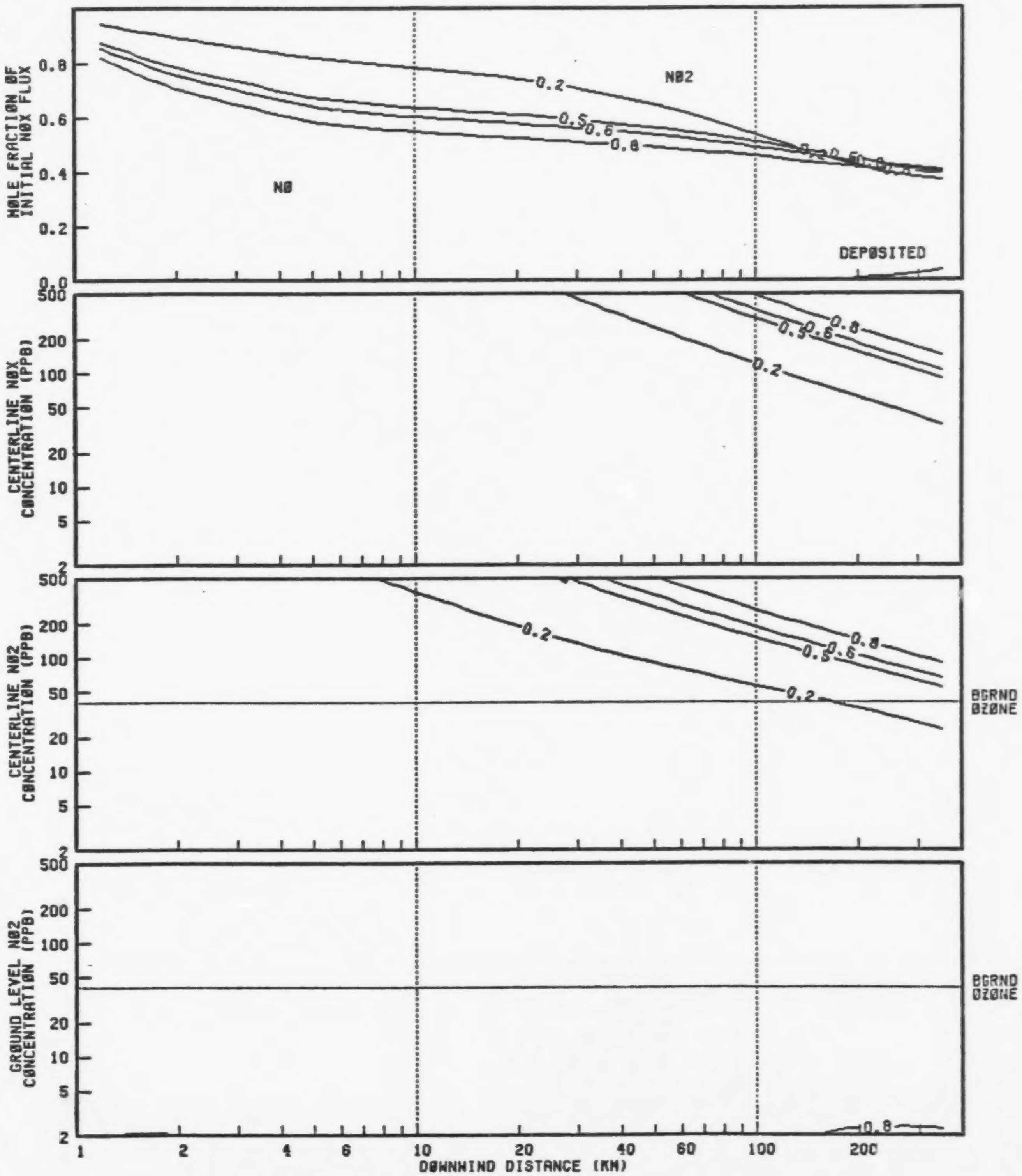
(b) Pasquill D Stability, 2.5 m/sec Wind, and 1000 m Mixing Depth

FIGURE C-2 (Continued)



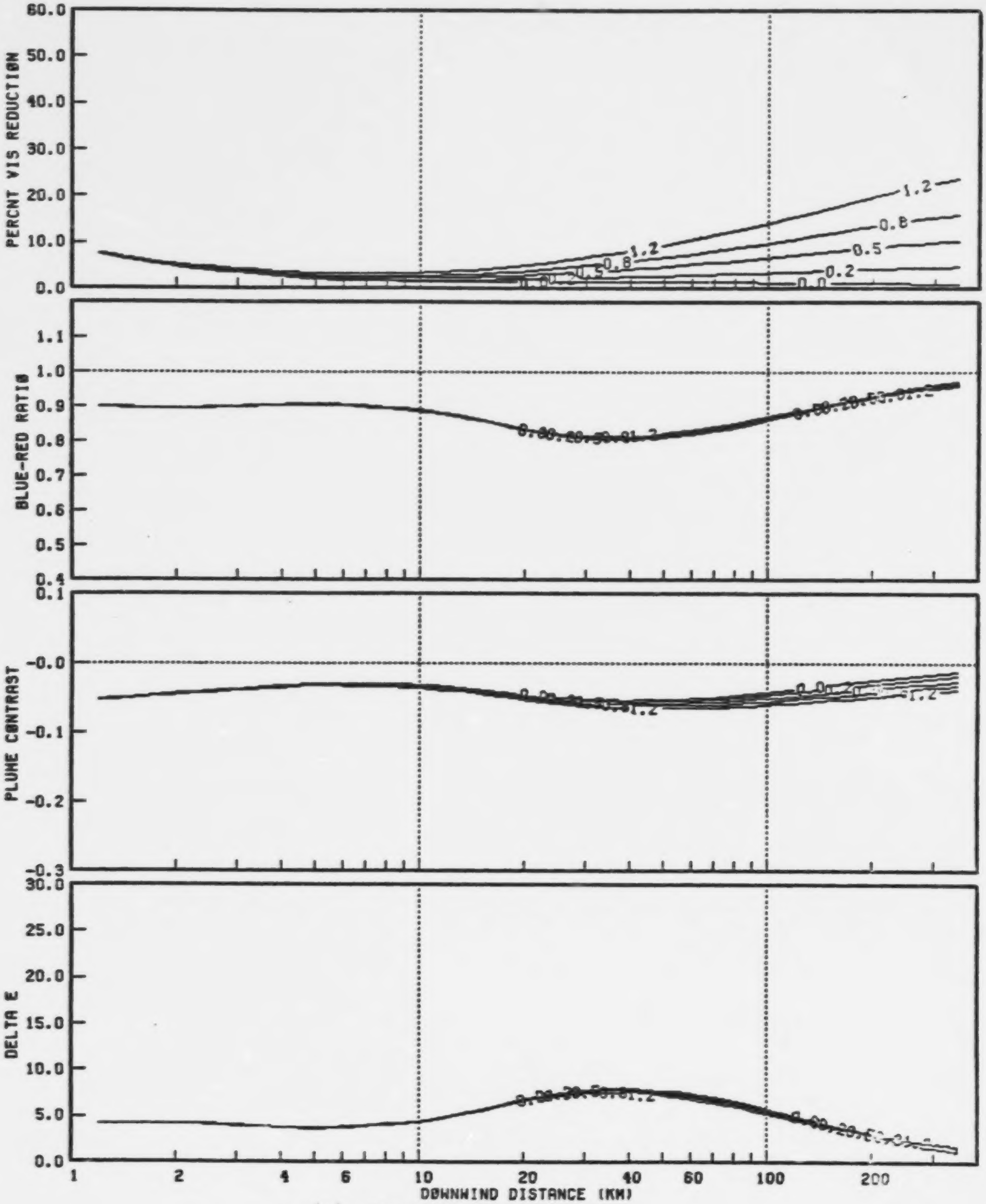
(c) Pasquill E Stability and 2.5 m/sec Wind

FIGURE C-2 (Continued)



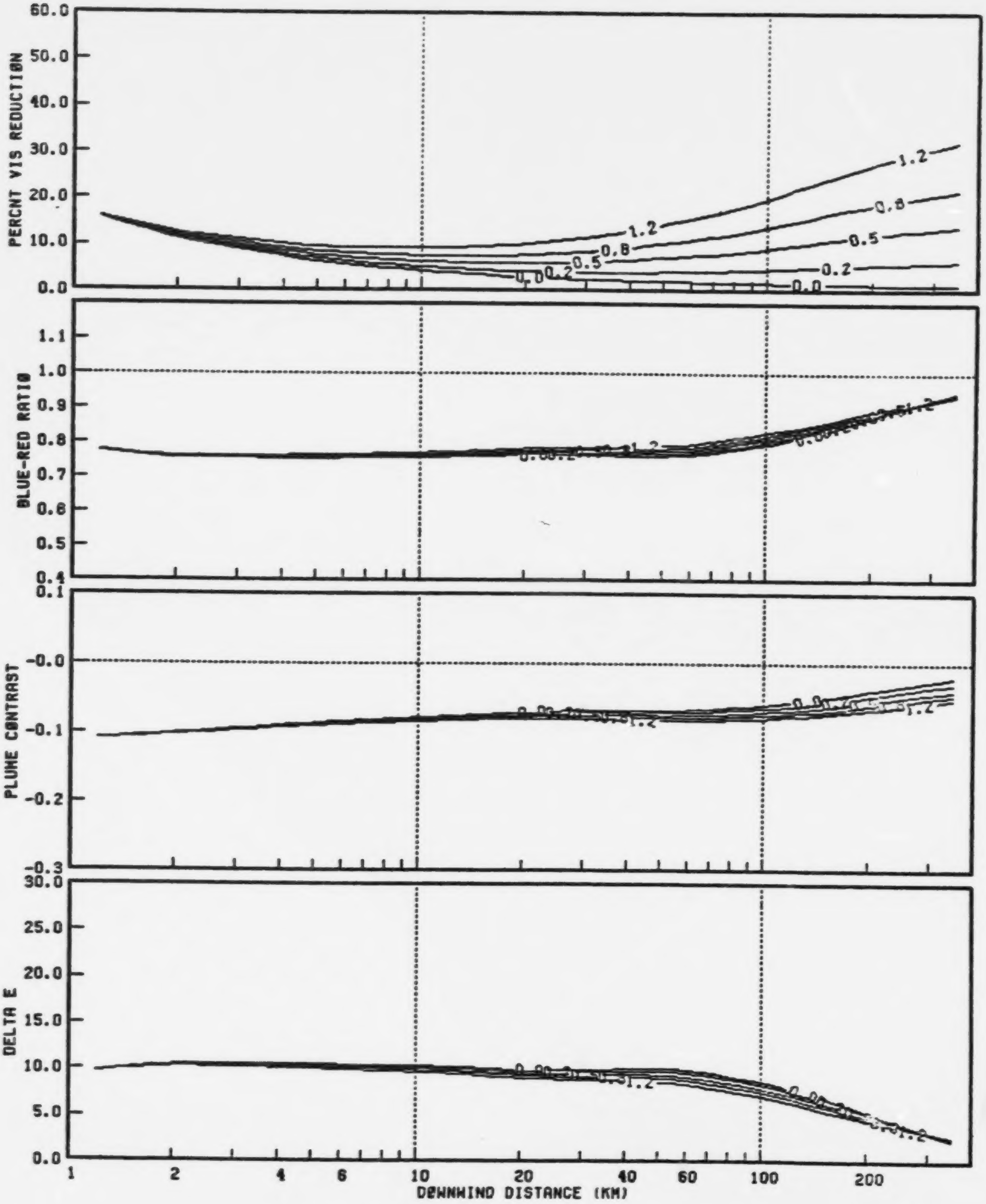
(d) Pasquill F Stability and 2.5 m/sec Wind

FIGURE C-2 (Concluded)



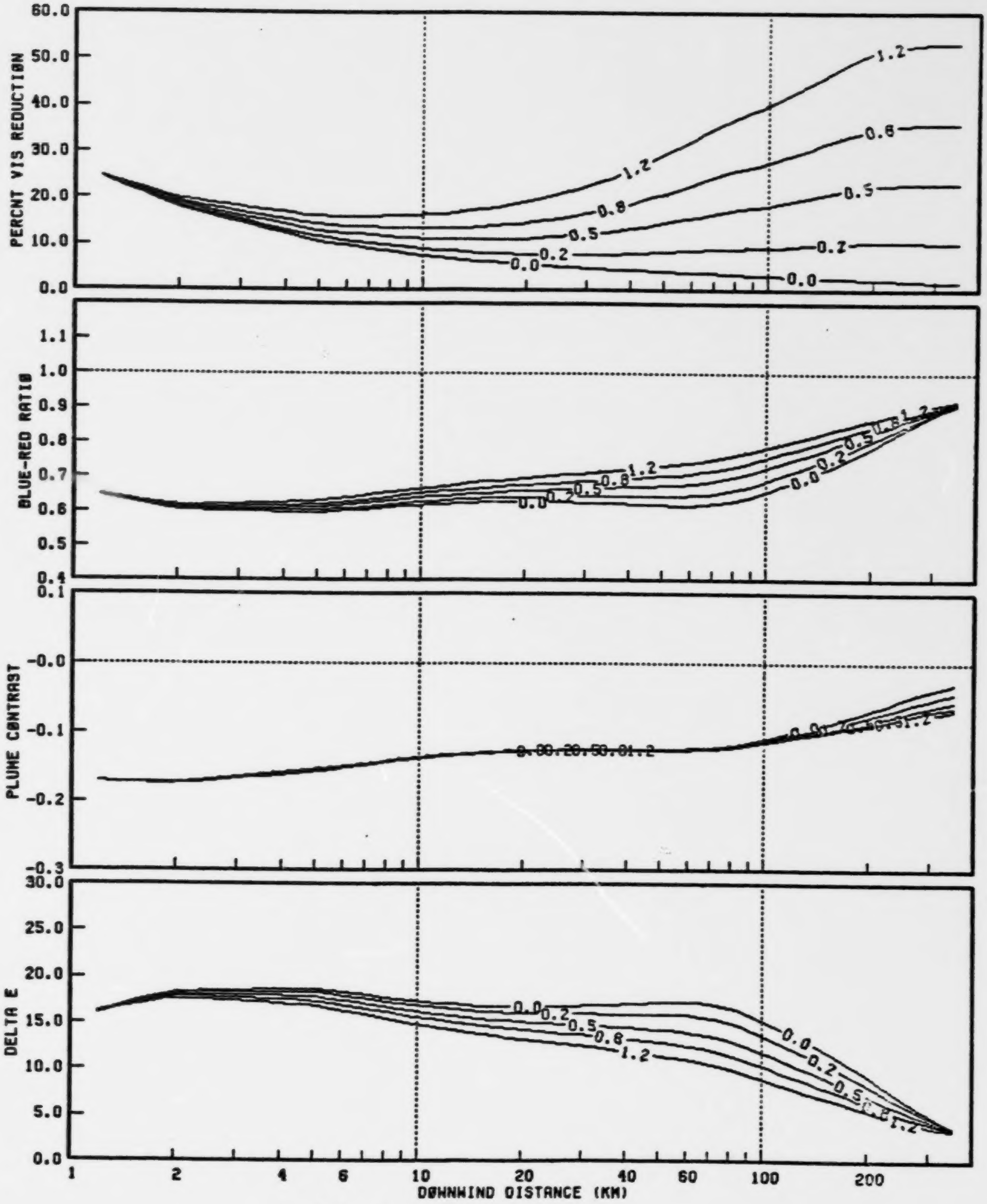
(a) Pasquill Stability C

FIGURE C-3. EFFECT OF $SO_2$ EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 3000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. $SO_2$ emission rates in pounds per million Btu are indicated.



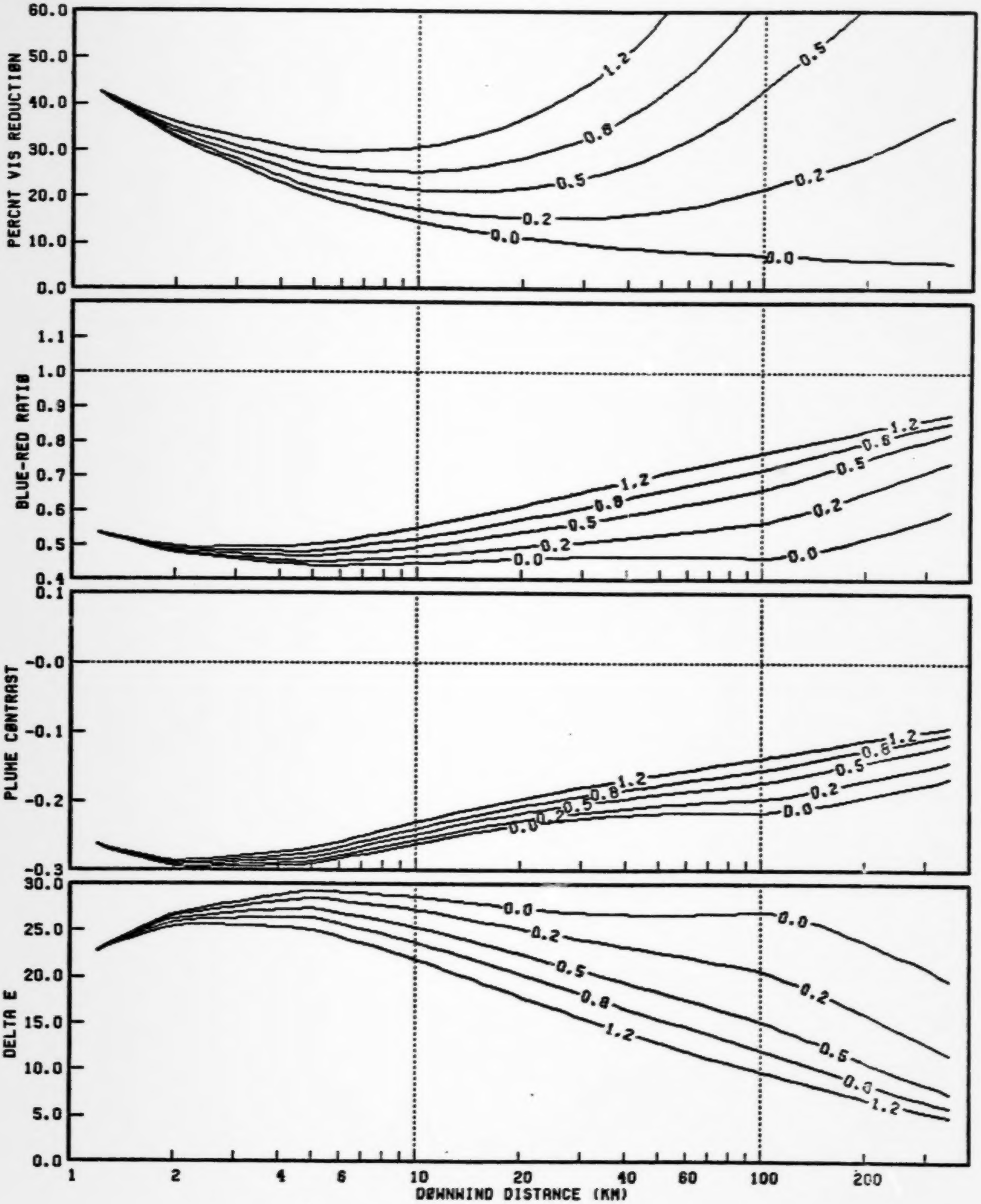
(b) Pasquill Stability D

FIGURE C-3 (Continued)



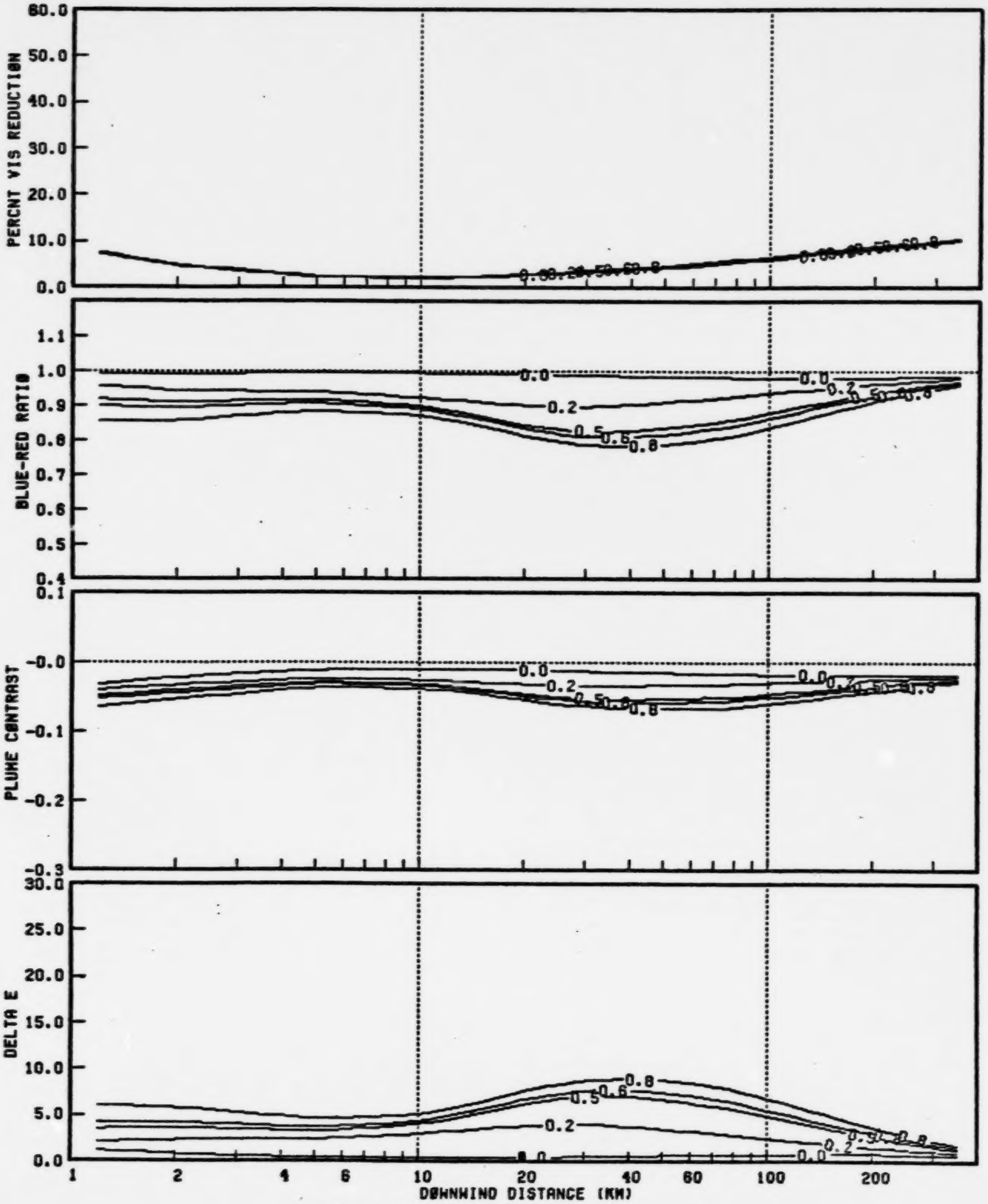
(c) Pasquill Stability E

FIGURE C-3 (Continued)



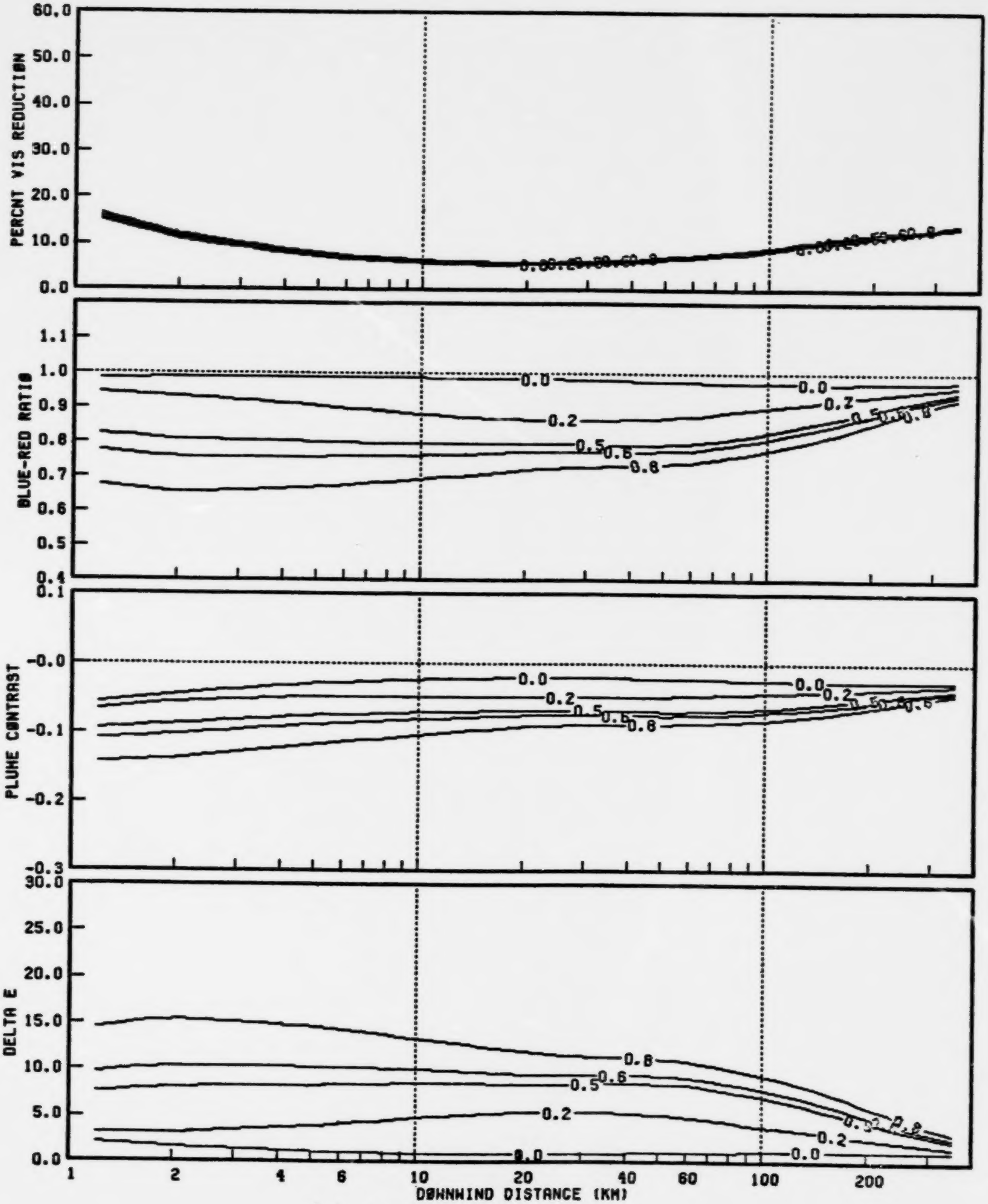
(d) Pasquill Stability F

FIGURE C-3 (Concluded)



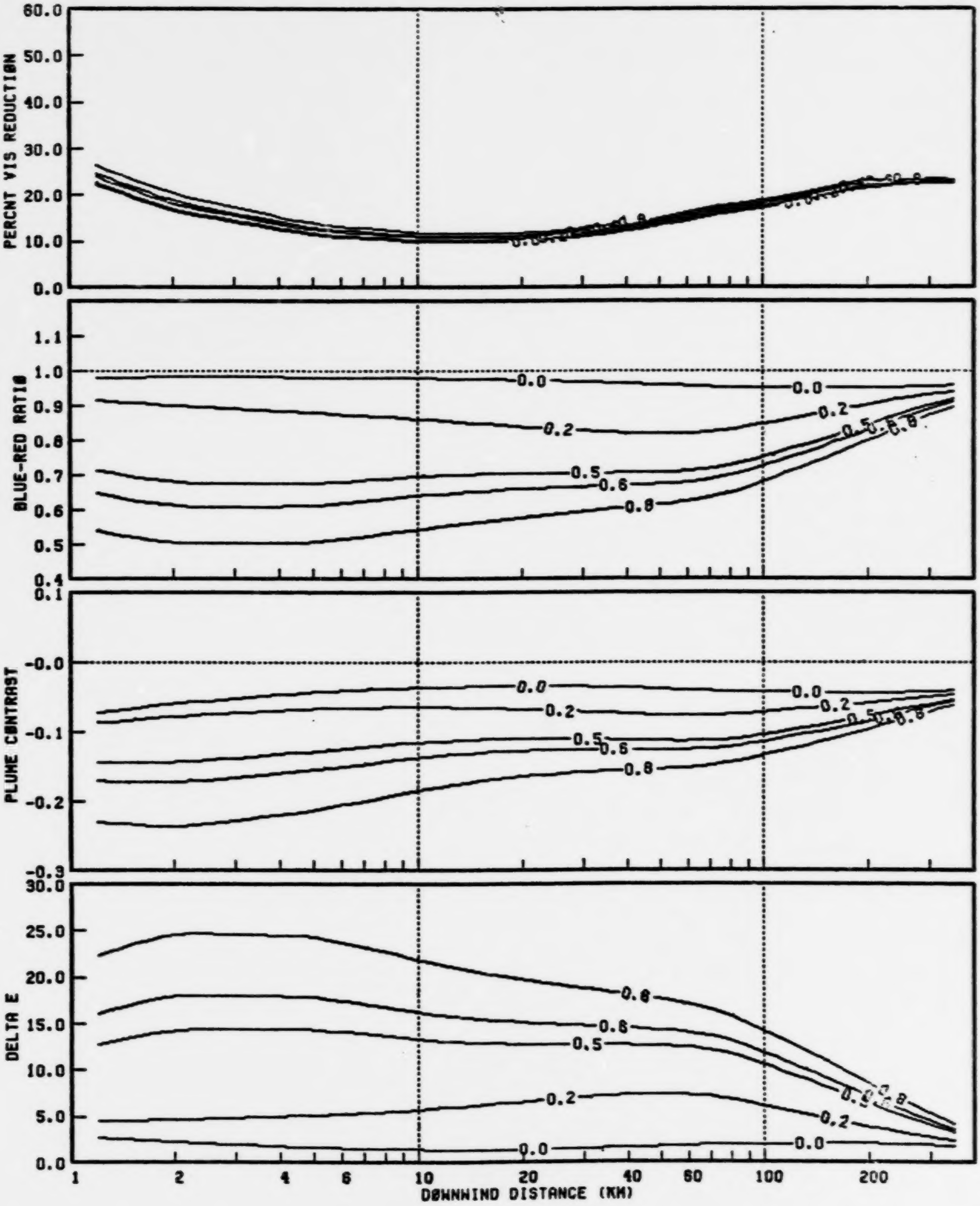
(a) Pasquill Stability C

FIGURE C-4. EFFECT OF $NO_x$ EMISSION RATE ON CALCULATED VISIBILITY IMPAIRMENT DOWNWIND OF A 3000 Mwe COAL-FIRED POWER PLANT ASSUMING A TYPICAL WESTERN BACKGROUND VISUAL RANGE. $NO_x$ emission rates in pounds per million Btu are indicated.



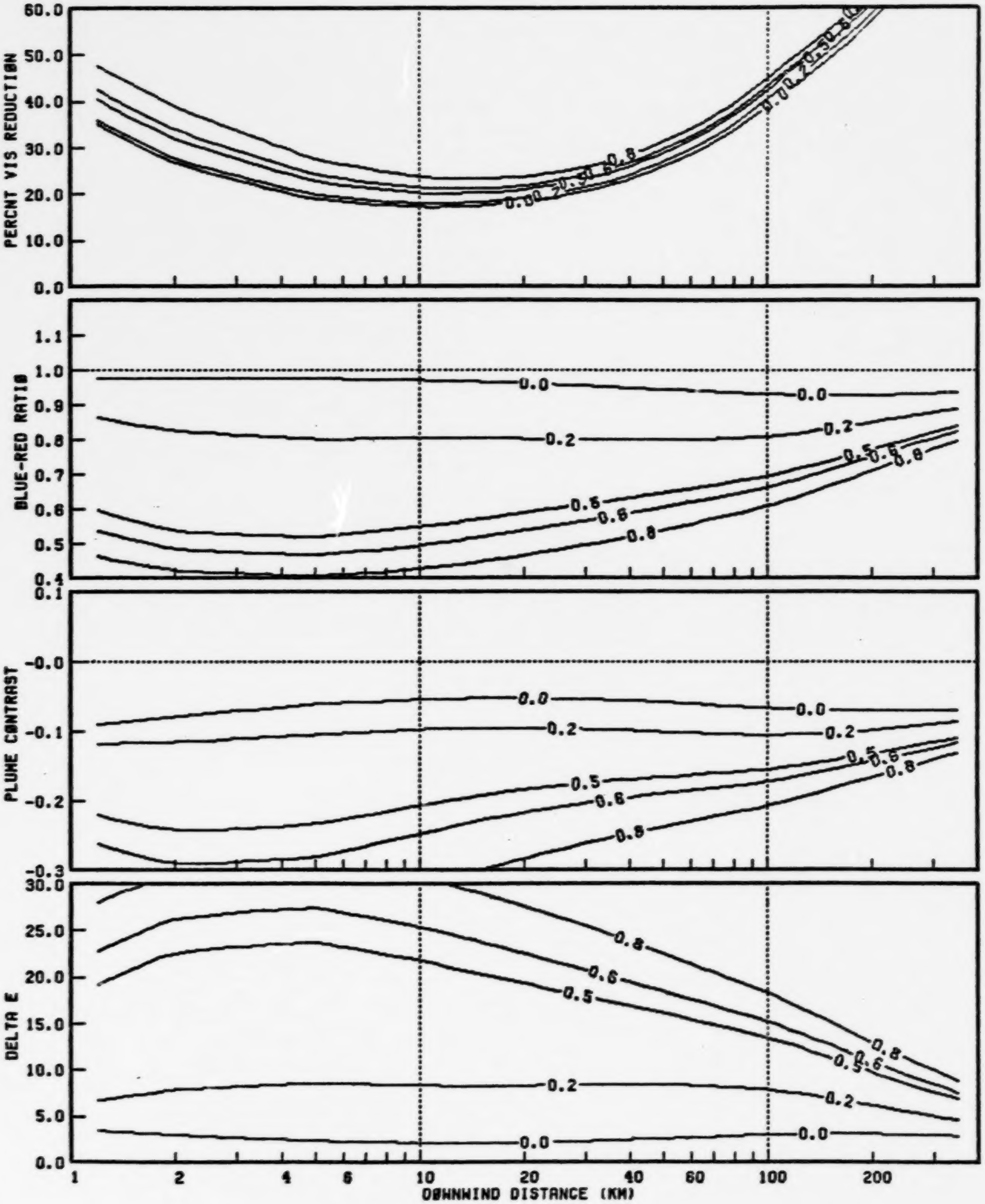
(b) Pasquill Stability D

FIGURE C-4 (Continued)



(c) Pasquill Stability E

FIGURE C-4 (Continued)



(d) Pasquill Stability F

FIGURE C-4 (Concluded)

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